VTT Technical Research Centre of Finland

Carbon footprint and environmental impacts of print products from cradle to grave

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Abstract

The aim of the LEADER project (2007–2010) was to study the environmental impacts occurring during the life cycle of print products. The scope of the project was focused on printed media products. The main products in the print media product group are newspapers, magazines, books and advertisements.

In the study, two research methods were applied: product-specific life cycle assessment (including carbon footprint) and the environmentally extended input-output model ENVIMAT (Seppälä et al. 2009). Life cycle assessment is a method that provides detailed information about the environmental aspects and potential environmental impacts connected to the life cycle of a product. Carbon footprinting is a fairly new application of life cycle assessment with its own specific calculation procedures.

In the ENVIMAT model, the life cycle impact results of the whole Finnish economy or individual industries can be presented with indicators such as environmental impact category results (e.g. climate change). Thus the ENVIMAT model is a macro-level tool that provides an estimate of the environmental impacts related to the production and consumption of print products in Finland.

During the project, data was collected concerning the whole life cycle of print products and five case products were selected for further study. Life cycle assessments were conducted and carbon footprints calculated for

- a regional newspaper (coldset offset printed)
- a weekly magazine (heatset offset printed)
- a photobook (printed with electrophotography).

Additionally, a carbon footprint study was conducted for

- an advertisement leaflet (rotogravure printed)
- hardcover book (sheetfed offset printed).

By selecting several case products, the potential impacts of different printing methods and different paper grades were included in the study. The case studies provide extensive examples of the environmental aspects and potential environmental impacts – and especially of the carbon footprints – of printed products. Insofar as this was possible, the case studies were defined to present viable value chains that could exist in Finland.

Due to several differences between the case products, the results of the studies are not directly comparable. However, the case studies point out many similarities and critical environmental aspects within the product group of fibre-based print products. Also the challenges related to the use of LCA and carbon footprint methodology to evaluate the environmental impacts of paper-based products have been illustrated and discussed in the context of the case studies.

In all cases, the LCI, carbon footprint and LCIA results are reported divided into life cycle stages and considering both direct and indirect emissions and impacts. By presenting the sources and potential impacts according to life cycle stages, the influence of different actors over the impacts of the whole life cycle can be evaluated.

The case studies provide new information about the potential environmental impacts related to print products. Especially the end-of-life treatments, all transport, manufacturing of printing ink and printing plates and the environmental impacts of electrophotography printing are aspects that have not been studied widely before. As part of data collection, the development of environmental performance within different printing methods was evaluated, and environmental indicators specific for the printing phase are discussed. Additionally, the results of the LEADER project can be used as help and background information when further developing methodologies and calculation principles suitable for fibre-based print products.

Preface

Concerns about climate change and the need to reduce greenhouse gas emissions have created pressures for actors in the print media value chain. Customers are willing to know and to minimize the carbon footprint of their purchases. Up-to-date information on environmental performance is also required in business-to-business relationships.

All kinds of product manufacture and consumption have environmental impacts. In respect to overall consumption, print media products do not have the greatest environmental loads. However, it is important to pay attention to every sector and product.

In 2008, the gross value of the Finnish mass communication sector's production was EUR 4.4 billion, representing four per cent of Finnish industrial output. Print media account for the largest share of mass communications, 67%. The main products are different kinds of newspapers, magazines, books and advertisements. On a daily basis, consumers read newspapers for 34 minutes, magazines for 19 minutes, and books for 25 minutes; they devote 167 minuts of their time to watching TV (Statistics Finland 2008).

In 2008, the circulation figures of print media products amounted to 13.7 million copies of magazines, 3.1 million copies of newspapers and 25.6 million copies of books (VKL & GT 2009). In the same year, the export value of the print media sector was EUR 265 million; the exports went to Russia, Sweden, Norway and other countries. The value of imports was almost EUR 200 million, with imported products coming mainly from Sweden, Germany and Great Britain. In Finland, there are about 2600 companies in the print media sector. Most of them are small and medium-sized enterprises (SMEs). (VKL & GT 2009.)

Typically, the main material of print products is paper. In Finland, the forest industry produces around 11 million tonnes of paper and paperboard annually. The bulk of the produced paper and board is exported (over 90%). According to the Finnish Forest Industries Federation's estimate, the value of the industry's production was about EUR 15 billion in 2009, of which some was generated by the EUR 11 billion by the pulp and paper industry in Finland. Forest industry products generated EUR 8.6 billion in export revenues. In 2008, the forest industry employed a total of 56,000 people, and 27,000 of them worked for the pulp and paper industry. (Finnish Forest Industries Federation, 2009a.)

This report provides information about the environmental impacts of print media products. Detailed information is important in order to improve sustainability performance. Furthermore, the aim is to generate new up-to-date knowledge for the print media value chain and the actors involved. The importance of life cycle thinking throughout the whole value chain stems from the principal aim of preventing possible environmental impacts from being transferred from one life cycle phase to another. Instead, the principle is to identify critical phases in the value chain and enable reduction actions throughout the chain.

This research report is not a full review of the environmental performance of print products. However we sincerely hope that the report provides comprehensive knowledge and a foundation for future research to tap potential opportunities in the environmental performance of the print media value chain.

The report is part of a larger research project, "Lean Development with Renewable Resources" (LEADER). The LEADER project (2007–2010) has been funded by Metsäliitto, Myllykoski, Stora Enso and UPM-Kymmene, Graafisen teollisuuden tutkimussäätiö (GTTS, The Graphic Industry Research Foundation) and The Finnish Funding Agency for Technology and Innovations – Tekes. The authors would like to thank all the companies for their valuable input on the research. We would also like to thank the printing houses and other companies in the printing value chain for the valuable information and comments they provided to us during the project.

Contents

Appendices

List of abbreviations

AOX	Absorbable organic halogens
BAT	Best available techniques
BSI	British Standards, National Standards body of the UK
CEPI	Confederation of European Paper Industries
CF	Carbon footprint
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq.	Carbon dioxide equivalent
COD	Chemical oxygen demand
CSWO	Coldset web offset printing method
CTP	Computer to plate
DIP	Deinked pulp
EP	Electrophotographic printing method
GHG	Greenhouse gas
GWP	Global warming potential
HSWO	Heatset web offset printing method
INGEDE	International Association of the Deinking Industry
IPA	Isopropanol, isopropyl alcohol
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LED	Light-emitting diode
LWC	Light-weight coated
N_2O	Nitrous oxide
NIP	Non-impact printing
Ntot	Total nitrogen

PAS 2050	Publicly available specification 2050:2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services
PE	Polyethylene, polythene, polyethene
PFC	Perfluorocarbon
PM	Particulate matter
Ptot	Total phosphorous
SC	Supercalendered
SFO	Sheetfed offset printing method
SME	Small and medium-sized enterprises
SO_2	Sulphur dioxide
SRA	Supplementary raw format A (formats for un-trimmed raw paper according to ISO 217:1995)
TMP	Thermo-mechanical pulp
TSP	Total particulate matter
TSS	Total suspended solids
TVOC	Total volatile organic compound
UV	Ultraviolet
VOC	Volatile organic compound

1. Introduction

Chapter 1 presents the background and objectives of the LEADER project – which ran from 2007 to 2010 – and introduces the contents of the report.

1.1 LEADER project 2007–2010

In 2007, KCL (Oy Keskuslaboratorio – Centrallaboratorium Ab) started a national-level research project in Finland called Lean Development with Renewable Resources (LEADER). The project was motivated by the increased concern over climate change as well as the introduction of the carbon footprint concept. At that time, the definition of "product carbon footprint" was not yet clear and calculation procedures involved a great deal of uncertainty.

Within KCL, research related to the environmental impacts of pulp and paper manufacturing and different paper products had been ongoing for years. Life cycle assessment was a central tool in evaluating the environmental impacts of products and technologies. However, most of the studies covered the product life cycle only up to the gate of the paper mill and information about the end use of products was often excluded. Greater interest towards the environmental performance of paper and print products from producers, customers (business) and consumers led to the need to expand the studies to cover the printing phase and end use of products. The LEADER project emerged in response to the lack of up-to-date data on printing processes or product end of life for the purposes of life cycle assessment in Finland.

The aim of the LEADER project was to study the environmental impacts occurring during the life cycle of print products. The scope of the project was focused on printed media products. The main products in the print media product group are newspapers, magazines, books and advertisements. Five case products were selected from among the printed media products:

- heatset offset printed magazine
- coldset offset printed newspaper
- sheetfed offset printed book
- electrophotography printed photobook
- rotogravure printed advertisement leaflet.

The selected case products differ from each other in several ways. By selecting different kinds of print products, the impacts of different paper grades and printing methods were included in the study. Since all these products have different manufacturing processes and uses, the purpose of the project is not to compare different print products, printing technologies or paper grades. Instead, the aim is to provide an overview of the environmental impacts of printed media products and the possibilities of reducing those impacts.

The objectives of the LEADER project were defined as follows:

- to create a holistic view of the environmental impacts of print products ver their whole life cycle
- to utilize LCA (ISO 14040-44) and carbon footprint (e.g. PAS 2050) methodology and calculations to identify the critical life cycle stages and processes in which the emissions can be reduced
- to enable product-specific and/or manufacturing process-specific calculations with the evaluation of improvements on the European scale
- to highlight positive aspects of fibre-based print products and to discuss challenges related to different calculation tools and sustainability evaluation methods
- to evaluate and demonstrate new ways of presenting carbon footprint and LCA results.

The project was coordinated first by KCL and then by VTT. Previous results of the LEADER-project (from years 2007–2009) have been presented and summarized in two intermediate research reports (Nors et al. 2009a and Nors et al. 2009b). In 2009, the research activities of KCL were merged with the Technical Research Centre of Finland (VTT). As a consequence, the coordination of the LEADER project was transferred to VTT.

The research work was conducted in cooperation with the Finnish Environment Institute (SYKE), Metropolia University of Applied Sciences, Finnmedia, several printing companies, suppliers, logistics companies and the paper manufacturers Stora Enso, UPM-Kymmene, Myllykoski and Metsäliitto. The project could not have been completed without the active participation of several paper and printing industry representatives and other actors from the print media value chain. Several cooperation partners from the industry have provided valuable information, data and comments during the project.

The project was funded by Stora Enso, UPM-Kymmene, Myllykoski, Metsäliitto, the Graphic Industry Research Foundation (GTTS) and the Finnish Funding Agency for Technology and Innovations (Tekes).

1.2 Contents of the report

The main results of the LEADER project are presented in two research reports:

- Carbon footprint and environmental impacts of print products from cradle to grave – Results from the LEADER project (Part 1). VTT Research Notes 2560, 2010.
- Communicating the environmental impacts of print products – Results from the LEADER project (Part 2). VTT Research Notes 2561, 2010.

This report (Part 1) presents the main results and findings of the case studies. Life cycle assessment (including carbon footprint) case studies were conducted for three print products: a newspaper, magazine and electrophotography printed photobook. Additionally, the carbon footprints (based on life cycle assessment) of an advertisement leaflet and hardcover book were calculated. Chapter 2 presents life cycle assessment as a research method. Carbon footprint is a fairly new concept and the calculation procedures are partly still under development. Important aspects of carbon footprint calculation for print products and available guidelines are presented in Chapter 2.

Each case is presented in its own chapter, including definitions of the case product, system boundaries and specific assumptions. In each case study, the sensitivity of assumptions and the importance of different parameters and factors are evaluated by applying different scenarios. The case studies are presented in Chapters 5–9. The case reports are designed to be independent of each other, which means that there might be some repetition in these chapters.

Since extensive data collection related to different printing methods was conducted during the project, the results of the data collection process and environmental indicators specific for printing are discussed in Chapter 3.

While life cycle assessment and carbon footprints provide detailed information about the potential environmental burdens of products, it was considered important to establish an overview of the environmental burden caused by the product group in general. For this purpose, the ENVIMAT model (Seppälä et al. 2009) was applied to evaluate the overall climate impacts of print production in Finland. ENVIMAT analysis is based on statistical product categories. In this context, the model provides information on the total climate impacts caused by print products in relation to housing and transport and other daily activities. The data is based on national-level statistics. The ENVIMAT model is described in Chapter 2 and the results are presented in Chapter 10.

Finally, the main results and conclusions are presented and summarized in Chapter 11. The chapter presents recommendations for the actors in the print media value chain and points out issues that require further study. The challenges related to life cycle assessment and carbon footprinting as research methods are discussed and future development needs are considered. In addition, the chapter considers the applicability and comparability of the results.

The second report of the LEADER project (Part 2) (Pihkola et al. 2010) discusses the challenges related to communicating the environmental impacts of products. It includes a literature review of available guidelines and tools for product-based communication and presents the development process of communication materials (fact sheets) that summarize the results of the case studies described in report 1. Qualitative research focused on the needs and challenges related to communicating the environmental impacts and carbon footprints of print products was conducted based on interviews with the actors in the print media value chain. (See Pihkola et al. 2010.)

As part of the project, a literature study entitled “Environmental performance of digital printing” was also published in 2010 as VTT research notes 2538 (Viluksela et al. 2010). A separate study focusing especially on electrophotography and inkjet was conducted since fairly little information on the possible environmental impacts of digital printing was available when the LEADER project was started. The objective of the literature study is to summarize the present situation and future prospects of digital printing technologies and markets, to review the existing publicly available information on the environmental impacts of digital printing, and to present suitable indicators for assessing the environmental performance of digital printing.

2. Methods

This chapter presents the basic principles and guidelines related to the applied research methods. In the study, two research methods were applied: product-specific life cycle assessment (including carbon footprints) and the environmentally extended input-output model ENVIMAT.

Life cycle assessment is a method that provides detailed information about the environmental aspects and potential environmental impacts connected to the life cycle of a print product. Carbon footprinting is a fairly new application of life cycle assessment with its own specific calculation procedures. Carbon footprinting is also a tool that is applied in product-specific calculations.

The ENVIMAT model belongs to the group of environmentally extended input-output (EEIO) models. In the model, the life cycle impact results of the whole Finnish economy or individual industries can be presented with indicators such as environmental impact category results (e.g. climate change, eutrophication), material flow indicators, value added and employment. Thus the ENVIMAT model is a macro-level tool that provides an estimate of the environmental impacts related to the production and consumption of print products in Finland.

2.1 Life cycle assessment

In the study, the environmental performance of different print products was evaluated using life cycle assessment (LCA) methodology. LCA analyzes the environmental aspects and potential impacts across the product life cycle from cradle to grave, including raw material acquisition, production, use, end-of-life treatment, recycling, and final disposal. LCA assesses the environmental impacts of product systems in accordance with the stated goal and scope.

Life cycle assessment is a technique that has been developed to gain a better understanding of the potential environmental impacts of products. LCA can help in

- identifying opportunities to improve the environmental performance of products at different life cycle stages
- informing decision-makers in industry, government or non-government organizations (for example, for the purpose of strategic planning or product design)
- selecting relevant indicators of environmental performance
- marketing products (for example, making an environmental claim or applying for an eco label). (ISO 14040:2006.)

The ISO 14040 standard addresses some of the requirements for carrying out an LCA (ISO 14040:2006). The principles of the LCA standard were followed when carrying out the case studies presented in this report. The four phases of LCA are the goal and scope definition phase, inventory analysis, impact assessment and interpretation. The four phases of LCA are presented in Figure 1.

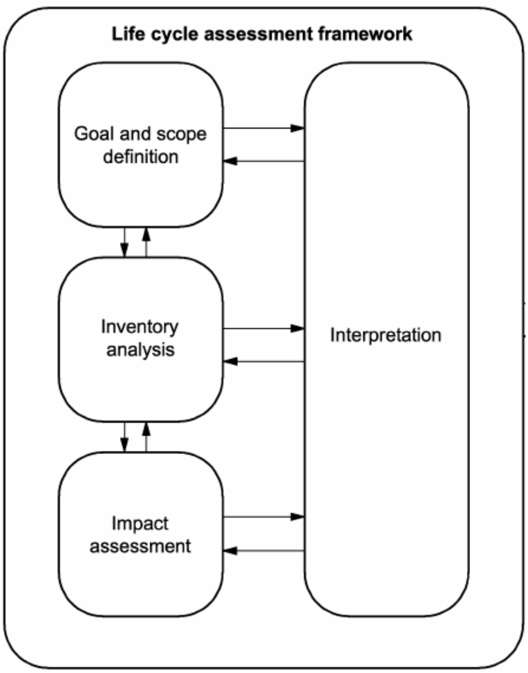


Figure 1. Four stages of LCA (ISO 14040:2006).

LCA requires handling, equating and balancing large amounts of data. In order to enable data handling, LCA calculation software (KCL-ECO) was utilized. The software describes different life cycle stages and processes along the life cycle in terms of modules and flows. Each module represents one unit of the process (or combination of processes), such as a sawmill, pulp manufacturing or printing. The features and functions of each module are presented by a certain number of logically related equations. In order to build up one module, information on all the inputs (raw materials, energy) and outputs (products, emissions, waste, by-products) related to the process stage needs to be collected and entered into the system.

2.1.1 Goal and scope definition

The goal definition phase determines the goal of a study: the intended application, the reasons behind the study, the intended audience and whether the results are intended to be used in comparative assertions for public disclosure. The scope includes information about the studied product system, the functions of the product system, the functional unit, the system boundary, the allocation procedures, data requirements, assumptions, limitations, initial data quality requirements and type of critical review (ISO 14040:2006).

An LCA study is structured around a functional unit that defines what is being studied. Thus, LCA is a relative approach. The functional unit is the reference value that forms the basis for comparisons between all inputs and outputs. In ISO 14040, the functional unit is defined as the *"quantified performance of a product system for use as a reference unit"* (ISO 14040:2006). In the case studies presented in this report, the functional unit was typically 1000 kg of products (e.g. newspapers) unless otherwise stated.

The scope, system boundary and level of detail of an LCA calculation depend on the subject and the intended use of the study. Thus the depth of the study can differ depending on its goal. As a consequence, the results of different LCA studies cannot be compared with each other without careful consideration of their functional units, system boundaries and assumptions related to calculations.

2.1.2 Life cycle inventory

Life cycle inventory is the second phase of an LCA study. The life cycle inventory (LCI) phase gives information about the inputs from the environment to the studied system and the outputs to the environment from the system. Data on each unit process can be classified as follows:

- energy inputs, raw material inputs, ancillary inputs and other physical inputs
- products, co-products and waste
- emissions to air, discharges to water and soil
- other environmental aspects.

After gathering the data, it is related to unit processes and to the reference flow of the functional unit (ISO 14040:2006).

2.1.3 LCI data collection in this study

Commonly, the life cycle inventory data (LCI data) consists of inputs and outputs. In the study, input and output data from printing and related processes were collected in order to conduct the life cycle assessment (LCA) and calculate the carbon footprints of the printed products from cradle to grave. Annual-level input and output data were collected between 2006 to 2009 from several printing companies participating in the research. The input data included printing materials (paper, inks, chemicals, etc.), water and energy. Output data consisted of products, different waste fractions and emissions.

VTT (previously KCL) coordinated the data collection and several engineering theses and internal research reports were written at the Metropolia University of Applied Sciences as part of the process. One engineering thesis contributed to the presented LCI data on HSWO printing (Kauhanen 2009), two of the theses contributed to electrophotographic printing (Peltonen 2008, Hopponen 2010) and one report concerned CSWO printing (Metropolia 2008). In addition, one thesis contributed to SFO printing (Perasto 2008) and one to the measurement of energy consumption during digital printing (Haanpää 2010). Furthermore, a student at the Helsinki University of Technology carried out a study concerning digital printing. Company-level accounting and reporting systems provided the basic data, which was verified and, if necessary, complemented. Printing houses with an environmental permit or environmental label disclose their environmental data annually, which facilitated data collection. Furthermore, a literature study was made concerning the environmental performance of digital printing (Viluksela et al. 2010).

Careful consideration was needed in order to make data from different sources usable and to ensure the reliability of the data. Some generalizations and assumptions were made when creating the generic data based on information collected from different companies and literature. Due to the confidentiality of the data, many of the data sources are anonymous and not specified in detail. Thus the data utilized or presented in the report does not concern any specific company. Rather, the report aims to provide figures that could be utilized as relevant data examples from the printing industry, indicating the current situation and general development trends.

Additional information was acquired from KCL EcoData and Ecoinvent LCA databases. VTT (previously KCL) has developed and maintains the KCL EcoData database for research purposes. The database contains over 300 modules including LCI-data related to pulp, paper and board manufacturing, printing, transports, wood and fibre supply, energy production, chemical and pigment manufacturing, recycling and energy recovery. Ecoinvent 2.2 database (developed and maintained by the Swiss Centre for Life Cycle Inventories) is a commercially available database that includes LCI-data from several industrial sectors (For more information, see http://www.ecoinvent.org/database/). All data sources and data age are presented in Appendix E.

2.1.4 Life cycle impact assessment

In the life cycle impact assessment (LCIA) phase, the significance of potential environmental impacts is evaluated using the LCI results. LCIA involves associating inventory data with specific environmental impact categories and category indicators. The mandatory elements in the LCIA phase are (ISO 14040:2006):

- selection of impact categories, category indicators and characterization models
- assignment of LCI results (classification)
- calculation of category indicator results (characterization).

In addition, normalization, grouping and weighting can be done.

In this study, the LCIA was performed using the ReCiPe Mid/Endpoint method, (version November 2009) (Goedkoop et al. 2009). ReCiPe is an LCIA method that is harmonized in terms of modelling principles and choices, but offers results at both the midpoint and endpoint level. In the midpoint-level assessment used in this study, emissions of hazardous substances and extractions of natural resources are converted into impact category indicator results for impact categories such as acidification, climate change and ecotoxicity. The endpoint-level assessment focuses on three endpoint indicators for the damage categories "damage to human health", "damage to ecosystems" and "damage to resource availability". The endpoint assessment involves many more uncertainties than the relatively robust midpoint-level approach.

The impact categories assessed in the newspaper, magazine and photobook cases were chosen on the basis of the extensiveness of the LCI data. For the newspaper and magazine, the following seven impact categories were included in the assessment:

1. *Climate change* refers to the warming of the climate as a consequence of an increase in so-called greenhouse gases.
2. *Acidification* is caused by emissions of sulphur dioxide and nitrogen compounds to the air. Acidification influences forest growth and the pH level of aquatic ecosystems. Acid deposits also damage building surfaces and other materials.
3. *Eutrophication* is caused by emissions of phosphorus and nitrogen to waterways. Eutrophication of waters refers to the increased growth rate of aquatic organisms and the increase in phytoplankton and water plants due to an imbalance in the aquatic ecosystem.
4. *Photochemical oxidant formation.* Photo-oxidants (such as ozone) are created from hydrocarbons and NOx in bright sunlight. High concentrations of ozone in the troposphere are harmful to both humans and plants.
5. *Particulate matter formation.* Emissions of small particulates are caused by industrial activities, energy production and traffic. Small particulates can penetrate deep into the lungs and cause respiratory disorders.
6. *Mineral resource depletion*.
7. *Fossil fuel depletion*. Depletion of non-renewable resources (fossil and mineral) is a topical issue that is particularly relevant to certain metals as well as fossil fuels.

Three additional impact categories were included in the case study for the photobook:

8. *Human toxicity*. Exposure to substances harmful to human health occurs in three ways: through drinking water and food, through the air we breathe, and through the skin. In addition to acute (i.e. sudden) and chronic (i.e. slowly developing) toxicity, other harmful effects include the risk of cancer, genetic changes and reproductive disorders.
9. *Terrestrial ecotoxicity*.

10. *Freshwater ecotoxicity*. Eco-toxicity (terrestrial and freshwater) refers to the harmful effects of dangerous chemicals on plants, animals and ecosystems. For example, toxic substances can make it more difficult for animals to breed.

The LCI parameters were classified and characterized into impact category indicator results according to the ReCiPe methodology. The impact category indicator results were then normalized against the impacts caused by one European inhabitant during one year. Normalized impact category results are dimensionless and enable the comparison of different impact category results against each other. The factors used for characterization and normalization can be found from the ReCiPe website (see http://www.lcia-recipe.net/). Figure 2 sketches the phases of an LCIA.

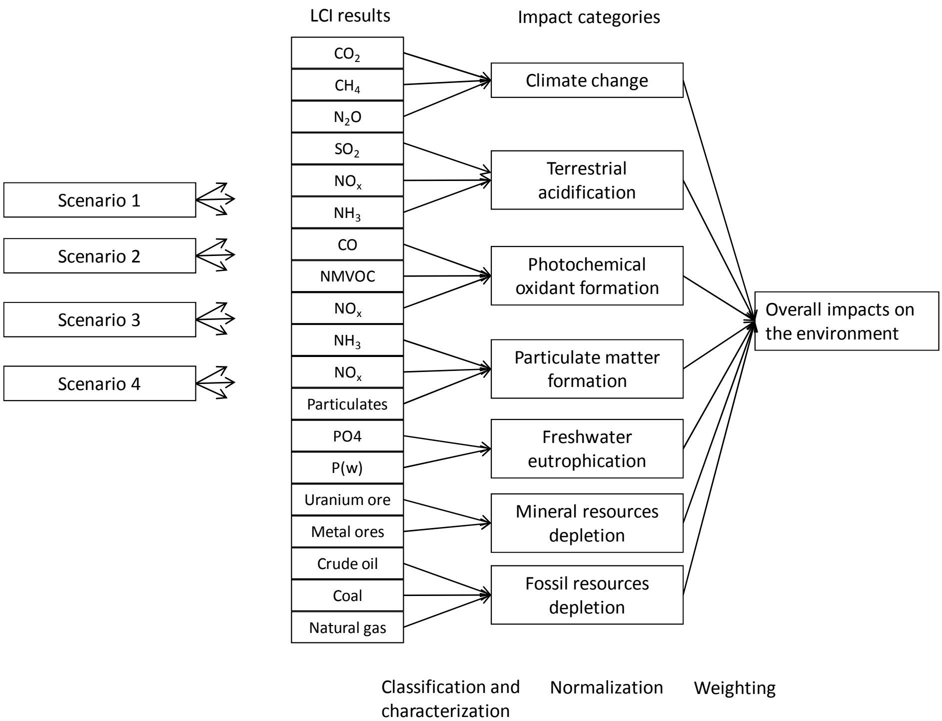


Figure 2. LCIA proceeds from classification and characterization of LCI results into impact category indicator results. Normalization is performed for the impact category indicator results. Weighting can be used to aggregate the impact category results into a single impact value describing the product system's overall potential impacts on the environment.

2.2 Carbon footprint

The carbon footprint calculation procedure is based on life cycle thinking and the life cycle assessment (LCA) methodology. Carbon footprint refers to the quantity of greenhouse gases (GHGs) produced during a product's life cycle. Greenhouse gas emissions are converted into carbon dioxide equivalents using 100-year global warming potentials. The carbon footprint case calculations in this report include all the greenhouse gas emissions that are mentioned by IPCC (see IPCC 2007, Forster et al. 2007) and in PAS 2050 (2008). However, the majority of the carbon footprint of a fibre-based print product is composed of carbon dioxide, methane and nitrous oxide. The global warming potentials of these three GHGs are presented in Table 1.

Table 1. Global warming potentials (GWPs) for different greenhouse gases (Forster et al. 2007).

Greenhouse gas	Global warming potential
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous oxide (N_20)	298

Even though the LCA methodology is standardized by ISO 14040 and 14044, the carbon footprint calculation procedure needs separate guidelines to cover carbon-specific features. Internationally accepted consistent methods for calculating carbon footprints are under development. Publicly Available Specification (PAS) 2050 'Specification for the assessment of the life cycle greenhouse gas emissions of goods and services', issued by BSI (British Standards 2008), can be regarded as the most credible and internationally recognized guidance at the present time, since ISO standardization work is still ongoing. Additionally, paper industry-specific guidance has been published by the Confederation of the European Paper Industry (CEPI 2007). The Ten Toes of the CEPI carbon footprint framework highlight the main stages of a paper product's life cycle that should be addressed in carbon footprint calculations.

2.2.1 PAS 2050

Publicly Available Specification (PAS) 2050 'Specification for the assessment of the life cycle greenhouse gas emissions of goods and services' is the first widely recognized guidance for carbon footprint calculation. It was published in

October 2008 by BSI (British Standards Institution). The development of PAS 2050 has been co-sponsored by Carbon Trust and the UK Department for Environment, Food and Rural Affairs (Defra). Several stakeholder groups, including CEPI, were given the opportunity to comment on a draft version.

PAS 2050 is based on life cycle thinking as defined in the ISO 14040 series (LCA standards). According to PAS 2050, all GHG emissions arising from fossil sources shall be included in CF calculations. Biogenic carbon is excluded except where it arises from land use change, is non-CO_2 (e.g. methane) or is stored in a product. Emissions are converted to CO_2 equivalent emissions.

PAS 2050 specifies requirements for identifying the system boundary, the sources of GHG emissions associated with goods and services that fall inside or outside the system boundary, the data requirements for carrying out the analysis, and the calculation of the results. It does not include category provisions for goods and services; however, it is determined that category-specific provisions for goods and services, developed in accordance with ISO 14025:2006, will be adopted where available. It is one of the intentions of PAS 2050 to allow for the comparison of GHG emissions between goods or services, and to enable the communication of this information. However, it does not specify requirements for communication.

2.2.2 CEPI carbon footprint framework

CEPI has launched a framework for issues that should be taken into account when calculating the carbon footprint of paper products (Framework for the development of carbon footprint for paper and board products, September 2007). Like PAS 2050, it is based on the life cycle inventory approach. The framework looks at direct and indirect emissions, carbon sequestration in forests and in products, the value of bio-energy and the concept of avoided emissions. It is based on ten key elements, which are called the Ten Toes of the carbon footprint. However, the framework allows individual companies to make different choices and does not provide guidance on methodological problems such as how to calculate carbon sequestered in forests. To complement the Ten Toes framework, CEPIPRINT and CEPIFINE have published a separate User guide to the carbon footprint of graphic paper v1.0 (CEPIPRINT-CEPIFINE 2010). The user guide is based on the Ten Toes and provides information on calculation methodologies and data sources that can be applied when calculating carbon footprint for graphic papers.

Ten Toes of the CEPI carbon footprint (CEPI 2007)

1. *Carbon sequestration in forests* – sustainable forest management (SFM) secures the stocks of carbon in forests so that they remain neutral or even improve in time.
2. *Carbon in forest products* – a product contains biomass carbon and as long as it is in use, it will keep this biomass carbon from the atmosphere.
3. *Greenhouse gas emissions from forest product manufacturing facilities* – generated from fossil fuel combustion at manufacturing facilities that produce forest products, including primary manufacturers and final manufacturing facilities.
4. *Greenhouse gas emissions associated with producing fibre* – for virgin fibre, this includes forest management and harvesting, and for recovered fibre, it includes the collection, sorting and processing of recovered paper before it enters the recycling process.
5. *Greenhouse gas emissions associated with producing other raw materials/fuels* – generated during the manufacturing of fuels and non-wood-based raw materials (e.g. chemicals and additives) used in manufacturing forest products and also direct emissions and emissions associated with electricity purchased to manufacture these raw materials.
6. *Greenhouse gas emissions associated with purchased electricity, steam, heat and hot and cold water* – emissions associated with purchased electricity, steam and heat used at facilities that manufacture forest products, including chip mills, pulp mills, paper and paperboard mills and final manufacturing facilities (e.g. box plants). This includes electricity for pollution control equipment used to treat manufacturing-derived wastes and emissions.
7. *Transport-related greenhouse gas emissions* – greenhouse gas emissions associated with transporting raw materials and products along the value chain. These include emissions from transporting wood, recovered fibre, other raw materials, intermediate products, final products and used products.
8. *Emissions associated with product use* – emissions that occur when a product is used. It is very uncommon for forest products to create such emissions. This is a key asset of forest products compared to for example electronic media.

9. *Emissions associated with product end-of-life* – emissions that occur after a product is used. They consist primarily of CH_4 resulting from the anaerobic decomposition of forest products in landfills.
10. *Avoided emissions and offsets* – emissions that do not occur (i.e. are avoided) because of an attribute of the product or an activity of the company making the product.

Currently, Toes 2–8 are included when calculating the carbon footprint of a paper product for business-to-business purposes (i.e. from cradle to gate) according to PAS 2050. However, Toes 2 and 8 typically do not affect the result since the use of paper products does not exceed one year (carbon stored in product) and the use of paper does not cause emissions. Toe 1 is currently excluded according to PAS and due to a lack of methods. Toe 9 will be included in cases whose scope extends from cradle to grave. Toe 10 is partly taken into account. According to PAS, offsetting is excluded. Offsetting means compensating GHG emissions by e.g. investing in projects that reduce the GHG emissions elsewhere. Offsetting can include e.g. investments in biobased energy or deforestation projects. However, avoided emissions in accordance with Toe 10 can be included. Avoided emissions occur when, e.g. a pulp mill provides surplus energy that is sold and used outside the mill for other purposes.

2.2.3 ISO 14067 Carbon footprint for products

The development of ISO standards for carbon footprints (ISO 14067 Carbon footprint of products – Part 1: Quantification and Part 2: Communication) started in January 2009, and the targeted publication of the standard is in 2011. According to the principles of standardization, the development of the ISO carbon footprint standard will not be based on any of the current guides, although they are taken into consideration. It is expected that once published the ISO standard will become the most important and globally used guidance.

The standardization work is naturally based on LCA standards ISO 14040-14044. Similarly to PAS 2050, all fossil GHG emissions will be included in carbon footprint calculations. At the time of writing, it is still being discussed whether the inclusion of biogenic carbon in the calculations should be optional or mandatory. However, it has been decided that if biogenic carbon is included, it will be reported separately from fossil carbon, showing transparently both removals and emissions. Removals will be shown as negative values. When the carbon is not turned into methane, the biogenic removals and emissions will equal zero. The amount of carbon stored in a product and the corresponding time period (product lifetime) will be reported separately. However, there are no plans to include a calculation rule to reduce the carbon footprint by the carbon storage impact in ISO 14067-1.

2.2.4 Critical issues in calculations for paper products

Calculating a carbon footprint involves choices and conditions that influence the final result. Many of them, such as allocation rules, system boundaries and data quality, appear in all calculations. When analyzing paper products, an additional specific feature causes questions and discussions: biogenic carbon.

Generally, carbon footprint calculations include only the GHG emissions originating from fossil sources. This is due to the fact that the biogenic carbon content on earth remains constant in the long run as a result of the carbon cycle, assuming that the total volume of forests remains the same. However, the amount of biogenic carbon in the atmosphere varies over time, depending on how much carbon is sequestered and stored in the forests at the moment, and how much is stored in forest products and landfills. At the regional level, carbon sinks have also either grown thanks to sustainable forest management or decreased due to deforestation. Managed forests sequester carbon dioxide from the atmosphere as they grow, whereas the net carbon sequestration of old forests is closer to zero because the amount of absorbed CO_2 equals the amounts of CO_2 released via the degradation of organic matter (Garcia-Gonzalo et al. 2007). On the other hand, there are studies that demonstrate that old-growth forests act as carbon sinks, even until the forests are 800 years old (Luyssaert et al. 2008).

Including biogenic carbon dioxide in carbon footprint calculations is challenging. The most relevant issues are the inclusion of the forest carbon balance and timeframe. Various approaches for including forest carbon sequestration in carbon footprint calculations have been presented (see, e.g. Kujanpää et al. 2009). Depending on the approach, the conclusion can be totally reversed to the advantage or disadvantage of the forest industry, and at the moment, none of the published methods is internationally and scientifically recognized.

Calculating biogenic carbon stored in products has received some acceptance, e.g. in connection to PAS 2050. According to PAS 2050, a weighting factor that represents the weighted average time of carbon storage is to be calculated if the product exists for one year or more. The carbon storage impact is included as a negative value in the assessment of GHG emissions arising from the life cycle of the product. The maximum benefit is gained if the carbon is stored in the product for 100 years or more. However, carbon storage is insignificant in the case of most paper products, because their life spans are usually relatively short. In a typical paper product case, the influence is 0–3% of the total emission figure. Books represent exceptions due to their relatively long life spans. As an example, carbon storage was calculated according to PAS 2050 for the book and photobook cases (see Chapters 7 and 9).

Since the methodologies are still evolving and there is no accepted way to, for example, include carbon sequestration and the forest carbon balance in the calculations, we have decided to follow the most recognized guideline, that is, PAS 2050. This means that biogenic carbon has a role when it causes non-CO_2 emissions (e.g. methane) or is stored in a product (books). Apart from these two exceptions, biogenic carbon is considered to be neutral. This approach is also in line with the foreseen ISO 14067 standard.

2.3 ENVIMAT – environmentally extended input-output model

The ENVIMAT model (Seppälä et al. 2009) describes the life cycle impacts of the Finnish economy at the macroeconomic level in 2002 and 2005. It includes the environmental impacts of 150 industries and also a number of socioeconomic aspects from the viewpoint of consumption and production. It also addresses how the Finnish economy causes environmental impacts abroad through imports, and the nature of the role of exports in domestic impacts. The ENVIMAT model was applied in the LEADER project to evaluate the climate impacts related to the production and consumption of print products in Finland.

The ENVIMAT model belongs to the group of environmentally extended input-output (EEIO) models. It is also a hybrid LCA model due to the use of LCA methodology for assessing the impacts of imports. The core elements of the model are monetary input-output tables (MIOT), physical input-output tables (PIOT), and environmental impact assessment. The life cycle impact results of the whole Finnish economy or individual industries can be presented with indicators such as environmental impact category results (e.g. climate change, eutrophication), material flow indicators, value added and employment. The content of the ENVIMAT model is outlined in Figure 3.

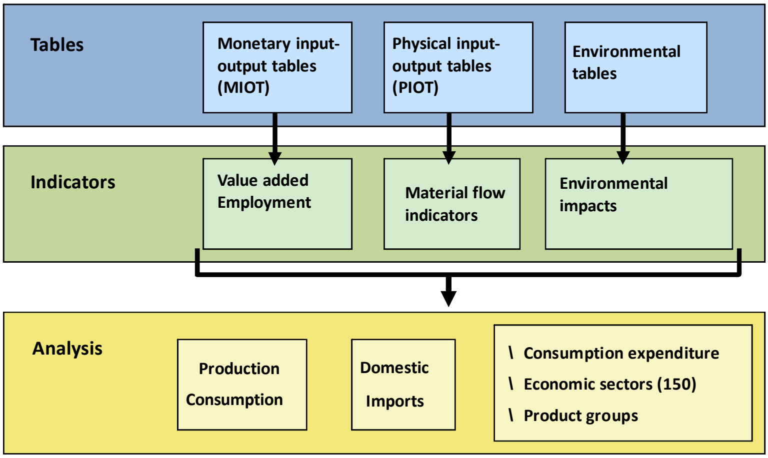


Figure 3. The structure of the ENVIMAT model.

The monetary input-output model is based on the supply and use tables of Statistics Finland. The tables are rather detailed, including 150 industries and 925 products. Furthermore, the use table is divided into domestic and imported products. All monetary flows between industries are defined using matrix calculation. The *industry*industry input-output model* for domestic products is solved from domestic supply and use tables. For imports a more detailed *product*industry* coefficient table with 722 imported products was applied.

The physical input-output (I/O) tables were constructed with the same dimensions as the monetary ones. In the physical I/O tables, the flows of goods are measured in mass units. The physical I/O tables are used to estimate the TMR (Total Material Requirement) indices for domestic production and imports and moreover to facilitate the application of LCI-type data to the environmental impact assessment of the model.

Environmental interventions (emissions into air and water, use of abiotic natural resources, land use) include altogether 74 emission variables. They were compiled for each domestic industry from the national emission inventories. The 74 environmental interventions were transformed into 10 environmental impact categories using characterization factors. The modified ReCiPe method (Sleeswijk et al. 2008) was used for the life cycle impact assessment (LCIA). However, in the context of this report, only impacts on climate change were considered.

2.3.1 Printed products in the ENVIMAT model

Two of the 150 industries included in the ENVIMAT model deal with printed products, namely Publishing (SIC 221) and Printing (SIC 222) (SIC = standard industrial classification)[1].

In the ENVIMAT model the results can be aggregated to 15 or 31 industries. Usually the results are presented by the most aggregated level, in which case printed products are included in the forestry sector among its various products. In the classification of 31 industries, the forestry sector is divided into three classes: Manufacture of wood and cork products (SIC 20), Manufacture of pulp, paper and paper products (SIC 21) and Publishing and printing (SIC 22). Furthermore, in the lowest aggregation level (150), sector 22 is divided into Publishing (221), Printing and service activities related to printing (222) and Reproduction of recorded media (223). In this study, the focus is on the Publishing and Printing sectors.

A single printed product cannot be found in the ENVIMAT model, but Publishing includes among others printed books and newspapers (Table 2). Printing mainly includes printing services for publishing houses and some other paper products. The results of both sectors are presented in this report.

Table 2. Product list of the publishing and printing sectors (Finnish Statistics, 2009).

SIC 221 Publishing includes the following products or services	**SIC 222 Printing includes the following products or services**
– Printed books, brochures, leaflets and the like – Newspapers, journals and periodicals – Records, tapes and other recorded media for audio media – Postcards, greeting cards, pictures and other printed matter.	– Newspaper and book printing services – New stamps; stamp-impressed paper; cheque forms; banknotes and the like – Trade advertising material, commercial catalogues and the like – Registers, account books, binders, forms and other articles of stationery, paper or paperboard – Bookbinding and finishing services – Printing plates or cylinders and other impressed media for use in printing.

[1] The Finnish term for SIC is *toimialaluokitus* (TOL).

2.3.2 Definitions of final and intermediate products

In the ENVIMAT model, the results of the industries cover only the final products of each industry, including all their life cycle impacts throughout the entire value chain. This is due to the fact that when the national economy is considered as a whole, overlapping must be avoided. For example, from the viewpoint of the printing sector: The life cycle impacts of the sector's final products (going straight to consumers) are shown as the results of the printing sector in the ENVIMAT model. On the other hand, the sector also produces printing services for other sectors e.g. the publishing sector. The impacts of these services are included in the results of the publishing sector, because they are part of the publishing sector's value chain. If they were included in both of the sectors, double counting would be unavoidable. The life cycle principle of the ENVIMAT model is illustrated in Figure 4.

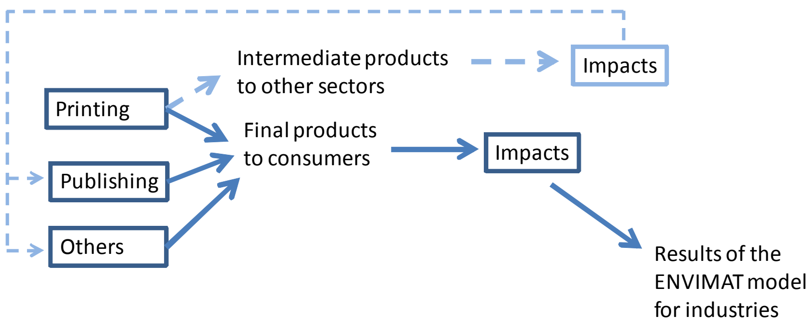


Figure 4. The ENVIMAT model approach to final and intermediate products. Dash line = intermediate product flows.

These life cycle results given by the ENVIMAT model differ from the national direct emissions that are reported in the domestic emission inventories. Therefore it is very important to understand correctly how the ENVIMAT results can be interpreted. Printing sector's results cover only 17 % of its total life cycle impacts, since intermediate products dominate. The share of intermediate products was approximately 83 %. In the Publishing sector the share of intermediate products is smaller, only 40 %, and thus the ENVIMAT results cover 60 % of the total environmental impacts of the sector.

Table 3. The shares of intermediate products/services of the Printing and Publishing sectors.

Sector	**Intermediate use**	**Final use**
Printing: products and services	83%	17%
Publishing: products and services	40%	60%

3. Environmental indicators for printing

The following chapter presents a short evaluation of the environmental indicators for printing based on the literature and the data gathered in the research. Furthermore, it is discussed how technology has influenced the environmental sustainability of printing. Finally, changes in the environmental performance of printing are considered in terms of energy and material efficiency.

3.1 Evaluation of indicators and environmental performance

The sustainability of a product, company or technology can be customized and improved. To this end, the change in sustainability should be defined and measurable. Sustainability indicators encompass environmental, economic and social indicators. Furthermore, industry-specific indicators that take into account the particular features of the industry are usually necessary. The indicators facilitate the measurement of sustainability performance and enable the evaluation of environmental impacts. They provide information for the compilation of the data that needs to be collected based on the regulations and legislation. Thus, the sustainability indicators provide information for communicating with the stakeholders and the authorities (Wessman & Pihkola 2009).

Climate change and GHG emissions are two of the most talked-about environmental issues of today. Furthermore, there is active discussion about resource scarcity, including water consumption. Obviously, indicators are needed. However, there is no single measurement or indicator that can be used to express the environmental performance of a printed product, printing company or industry.

It is essential for a printing house to choose the right indicators to follow. It is not a simple task to define indicators, and their importance and applicability should always be checked to ensure that all the relevant information will be collected. Thus the choice of indicators also depends on which issues are of most interest. Also, the availability of monitoring systems has an impact. The relevant indicators might also differ between different printing methods, since for example the amount of chemicals utilized in the process varies significantly from one method to another. (Viluksela 2008, Wessman & Pihkola 2009, Pohjola 2005, Enroth 2006.)

In earlier studies, several indicators have been used to describe the environmental impact of printing. The environmental loads of the printing processes were first studied in detail in the 1990s (See e.g. Juntunen et al 1994; Dalhielm & Axelsson 1995; Westren-Doll et al. 1997; INFRAS 1998). Print industry-specific indicators are proposed by the comprehensive studies of Pohjola and Enroth (Pohjola 2005, Enroth 2006 and Enroth 2001). The studies propose environmental indicators for the fields of energy, water, materials, transportation, emissions and waste. Pohjola also presents economic indicators for the costs of energy, water, transportation and waste, and Enroth outlines models for social indicators for the share of customers satisfied with the company's environmental performance.

At the beginning of the LEADER project, a study was carried out on the development of environmental sustainability of different printing methods. This study concentrated on conventional printing methods and was presented and published in the Iarigai conference 2008 under the name "Changes in sustainability due to technology development in selected printing processes" (Viluksela et al. 2008). In this Chapter, a summary of the results previously published in the Iarigai paper (Viluksela et al. 2008) is presented. Since 2008, the results have been updated based on new data collected during the project.

The second literature study made in this project – called "Environmental performance of digital printing" – was published in 2010 as VTT research notes 2538 (Viluksela et al. 2010). The study reviews the existing publicly available information on the environmental impacts of printing, especially digital printing, and it presents suitable indicators for assessing the environmental performance of digital printing. Main findings of the literature study are summarized later in this chapter.

For expressing environmental impacts, it is necessary to relate the input and output data to a functional unit related to the volume of production. Many studies have used the most common functional unit, one tonne of printed products. Other functional units are (millions of) square metres of printed products and tonnes of paper consumed. The former reflects the nature of printed products –

printed pages are more closely related to paper surface area than weight – and the latter may be easier to account for, since the weight of products may not always be recorded. In digital printing, the functional unit of 100 A4 pages is also used. The functional unit applied in this study was 1000 kg of printed products (unless otherwise stated). The main input and output categories of the printing process are presented in Figure 5.

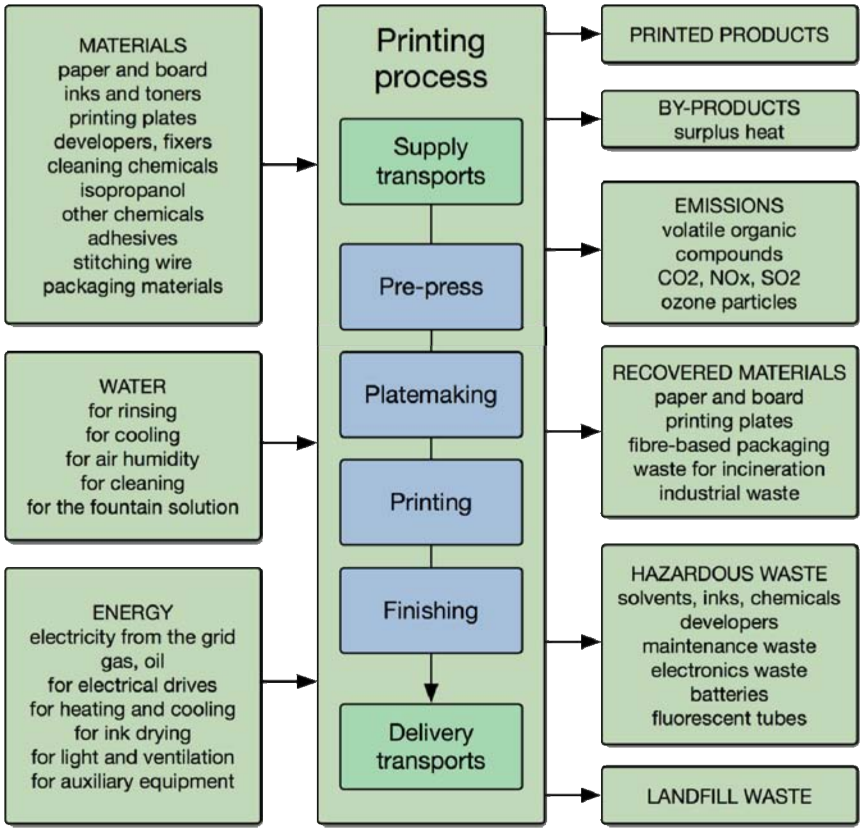


Figure 5. Example of inputs and outputs of the printing process (picture is a combination based on the work of Viluksela 2008, Kauhanen 2009, Peltonen 2008, Perasto 2008).

To be able to utilize the input and output data in product based LCA or carbon footprint calculations, the data needs to be allocated to different products. If most of the products are similar in size and used materials, the allocation based on annual statistics might be simple. If there is great variation between different products, the allocation becomes more challenging and special monitoring and reporting is required. Achieving accurate product based information is essential when evaluation of environmental performance of product is conducted.

3.1.1 Environmental indicators selected for our study

The printing industry-specific indicators used in this research focused on energy and material consumption. Energy consumption is one of the main indicators for assessing the environmental performance of printing houses. The growing need for carbon footprint information will likely increase the demand for energy-saving solutions and products in the future. Carbon footprint assessment is also closely related to both of the key issues of the study, namely the use of energy and materials. (Viluksela et al. 2008.)

During the LEADER project, input and output data was collected from several printing houses and from the literature. The collected data was utilized in the LCA and carbon footprint case studies presented in this report. Additionally, the data was used to have an overall view about the consumption of energy and raw materials in different printing methods. The values of the selected indicators, based on the collected LCI data from different printing houses and literature, are presented in Table 4. The calculation principles for the presented indicators and values are presented in Appendix A.

In the Table, the values are presented as a range or as variation between different printing houses. The variation is dependent on the production (variation of products, the run lengths) in the printing house, the data years, the machinery and work habits. Furthermore, the values should be considered to be indicative of the levels of consumption. On the basis of the table, different printing methods cannot be compared directly. Rather, it presents the magnitude of the indicators. To make the indicators presented in Table 4 more useful for a printer in evaluating the environmental performance of a product, all the indicators should be product-specific or product group-specific instead of general. Some reasons why the figures for different methods should not be directly compared are explained after the table.

Table 4. Estimated data values for the selected environmental indicators. All figures are expressed per one tonne of printed products. NA means not available.

Indicator	Unit	Coldset web offset	Heatset web offset	Sheet fed offset	Gravure	Electrophotography	High speed inkjet
Energy consumption	kWh/tonne	420-500	750- 850	800-1040	590- 650	300-700	450-800
Paper consumption	tonne/tonr	1.06- 1.1	1.2-1.24	1.1-1.3	1.09-1.14	1.05-1.17	1.06-1.11
Ink consumption (CMYK)	kg/tonne	14-20	26-32	5-8	22-50	11-39	10-40
VOC emissions (estimate)	kg/tonne	0.1-0.3	0.5-0.6	3.0-5.3	1.2 -1.9	NA	NA
Material for recycling and recovery use	%	95-98%	96-98%	95-97%	96-99%	98-99%	NA
Hazardous waste	kg/tonne	2.7-3.0	1.8-2.0	1-6	0.98-1.1	0.4-1.3	NA
Data sources (years 2006-2009)	Printing houses in Finland	5	2	4	KCL2008 and Ehnroth 2006	5	3

Energy consumption

The energy consumption figures are focused on the energy use of printing houses in the different stages of print product manufacture (prepress, press and post-press operations). Energy consumption in a printing plant can be divided into a basic part, e.g. heating of premises, and a variable part, e.g. running of production machines. Although most printing companies only monitor total electricity consumption at the plant level, it would be possible to measure the consumption of different machines. In addition to electricity, the consumption of gas or other fuels and purchased heat should be monitored. However, it should be noted that it was rather challenging to obtain accurate and separate figures for energy consumption. Thus, some of the figures are estimates, which introduces variation.

In the study it was requested that energy consumption be divided between production machinery (e.g. printing press, dryer), auxiliary equipment (e.g. pressurized air supply, cooling of fountain solution, incineration of exhaust gases) and the printing plant building (e.g. lighting, ventilation). In many cases, it was somewhat difficult to achieve this level of accuracy. Thus, it is becoming more important to measure these issues separately. Different kinds of monitoring devices for energy consumption are increasingly available. In the future, such monitoring devices – or displays and online information – can be incorporated into machines, production and office spaces.

A study concerning energy consumption indicated that print production accounted for 40% of the consumption of a building and its heating, ventilation, lightning, etc. for 60% (Westren Doll et al. 1997). Another study gave information concerning printing presses, where ink drying, the main drive and air supply accounted for the largest share of energy consumption (Heidelberg 2008, Jepsen & Tebert 2003). Detailed information on energy consumption in digital printing was sought. The engineering thesis of Haanpää (2010) provided some new information, but also showed how difficult it is to measure detailed information if the log of the press does not have integrated measurement functionalities.

Accurate energy consumption data could be very helpful in enabling printers to achieve better energy efficiency. It would be helpful to have monitoring devices or displays that give detailed information on plant energy consumption or a reporting system that facilitates the monitoring of the energy consumption of different kinds of production and specific products. Consequently, this could help the printer to identify where to achieve the greatest reductions in energy consumption.

Paper consumption

Paper consumption varies depending on, for example, the type of printing method, type of print products and print run length. Furthermore, it should be reminded that the production scale of different printing methods varies from very high volumes to very low volumes (e.g. gravure versus electrophotography). If the consumption of materials such as papers is followed at a general level on an annual basis, it is very difficult to gain information on specific products or product groups and to calculate information on indicators such as the carbon footprint.

The allocation of material consumption to a product group or products is an important part of serious actions to improve resource efficiency and decrease the environmental load of products. This will also help in the identification of the differences between different kinds of products (which vary in size, quality, complexity and volume) in terms of environmental performance. For instance the follow up of maculature amounts is essential. The effect of maculature is twofold; on the one hand, it is important to decrease it efficiently, and on the other, it can be recovered and recycled.

Ink consumption

Comparing only the amount of the ink used can lead to misinterpretation. For example, depending on the type of product, the amount of colour pictures or the combined characteristics of paper and ink introduce variation within a single method. Furthermore the conventional inks used in the different methods vary remarkably. In heatset web offset, the solvent from the ink is evaporated from the web and the air is cleaned with an afterburner. In coldset offset the ink does not dry, but rather sets to the porous material, such that all the ink applied to the web stays there. In sheetfed offset, the ink dries by polymerization and the pigmentation rate of the ink is very high. Also, the paper used is dense and thus the ink remains on the surface of the paper.

In rotogravure, the ink solvent content is very high and the solvent is recovered in the process by means of active carbon filtration. Also, in electrophotography, all the toner stays on top of the paper, where it is fixed by pressure and heat, but the paper might be more porous than that used in SFO. In inkjet, the ink is dried by heat and the solvent is evaporated. Furthermore, UV- and EB-curable inks can be used in several different printing methods. These inks are not included in the LCI data; and the figures and environmental burden of these inks would be different.

VOC emissions

The amount of VOC emissions (in Finland 2006–2007) was estimated partly on the basis of measured level of emissions, and partly on the basis of consumption of inks, chemicals (washing agents, fountain solution additive) and isopropanol, taking into account the concentration of VOCs in different chemicals and isopropanol. Using both estimates and measured results introduces variation in the results.

For the past few years, the trend in the use of isopropanol in offset printing has been towards non-alcohol printing. It means that instead of isopropanol, another substitute is added to the fountain solution of the offset process to lower the surface tension of water. None of the printing houses in this study were totally alcohol-free in all of their printing, but there were differences between the presses. A very high percentage of presses are still using isopropanol, but the IPA concentration is very low. Furthermore, waterless offset printing is still entering the offset market and was not included in the LCI data.

Comprehensive information about VOC emissions is available, e.g. in the Reference Document on Best Available Techniques on Surface Treatment using Organic Solvents, published by the European Integrated Pollution Prevention and Control Bureau in 2007 (EIPPCB 2007, Antson et al. 2008, SFS 2005).

Material for recycling and hazardous waste

Most of the materials in the printing house are either recyclable or recoverable (e.g. paper, board, aluminium plates, copper, etc.). One reason for this is that paper – the major base of the product – is recyclable. In this respect the amount of chemicals is in a minor role. However, the importance of chemicals should not be forgotten. The characteristics of chemicals influence their significance from the perspective of product safety, environmental harmfulness and load. In addition, a high print production volume might lead to a high usage volume of chemicals. The importance of the follow-up and selection of environmentally friendly chemicals cannot be neglected. Furthermore, the volume of hazardous, landfill and other such wastes is small thanks to effective waste sorting.

Digital printing techniques, particularly electrophotographic printing (EP) and high-volume inkjet printing, are commonly regarded as environmentally friendly alternatives. According to our study more research is needed before blindly adopting this belief. It is true that digital printing does not use printing plates. Therefore, there are neither plate processing chemicals nor waste plates and chemicals to deal with. Also, in most EP applications, printing is based on dry toner technology, which considerably reduces the amount of cleaning solvents used for press cleaning.

As a result of intensive maintenance needs, several waste fractions are produced in digital printing: used supplies and containers (such as waste toner, toner and fuser oil cartridges) and press parts (for example, imaging drums or belts). Some of these fractions are classified as electronic waste. Since the press manufacturer handles disposal and recycling, it is difficult to gather information on the amounts of these waste fractions.

3.2 Towards more environmentally sustainable print production

If technology development embraces sustainability, a change towards more sustainable print media can be expected. Today's modern presses and printing processes are faster and more automated than ever before. New materials and printing process chemicals have become available and the workflow of making prints has fewer steps.

The graphic arts industry has gone through radical changes in the field of digitalization and automation during the last two decades. Digitalization continues apace. All in all, many of the technical and process development initiatives launched in the past two decades contribute to the improved environmental performance of printing processes. A summary of recent technical and process development was compiled from the literature and interviews with industry experts and then connected to environmental performance. This summary can be found in Appendix B.

In spite of the modern, fast and radical new technology adopted by printing houses, it is necessary to engage in the systematic follow up and reporting of material and energy flows. This is done in order to obtain accurate data about the environmental performance of printing processes and to be able to improve them. Print product-specific information about resource efficiency (energy and materials) is especially necessary. With the help of new technology solutions and calculation methods, information on the environmental performance of printers can be obtained more easily and rapidly than before.

Printing houses need to accurately report product specific-data, and device manufacturers and suppliers should help them in this effort. This need arises from the expectation that printing houses and consumers will be increasingly interested in the environmental performance of different products. Thus, it is even more important to consider environmental sustainability aspects as part of future operations combining novel technologies and new empowered services.

3.2.1 Mechanical printing methods

Many technological improvements are connected to the printing equipment and devices. Such improvements are adopted in connection with new press investments. Some technical solutions can also be retrofitted to existing equipment.

Some improvements are workflow- or process-related and as such easier to implement.

The technical developments and innovations seen over the past 15 years are clearly reflected in improved energy efficiency. Press technology development has contributed to improved energy efficiency, such as in the case of direct drives and the incineration of HSWO exhaust gases. HSWO dryer exhaust gas purification technology has evolved considerably and a regenerative thermal oxidizer integrated into the dryer has been developed. (Viluksela et al. 2008, Heidelberg 2008, Painomaailma 7/2002, Ernst & Young 2007, Manroland 2008, PrintCity 2008a.)

Furthermore, technological developments leading to improvements in material efficiency include, for example, automation of makeready operations and production as well as digital workflow. Makeready operations, register control and colour control have all benefited from technical development and become more automated. Modern web and sheetfed presses feature closed loop colour control. Automatic blanket washing devices have also become a common technology. These developments have improved material efficiency and productivity. (Viluksela et al. 2008, Heidelberg 2008, Manroland 2008, Haugen 2000, Pesonen 2008, Päivinen 2008.)

The development of new types of UV- and EB-curing inks has increased print quality but there is not enough knowledge of the environmental impact of the inks. The environmental effect of manufacturing and disposing of these inks is still an open question.

Future environmental improvements in mechanical printing methods will probably take place in the areas of energy-efficient drying techniques and greater efficiency in the use of materials and supplies, especially paper.

3.2.2 Digital printing methods

The development of inkjet and electrophotography technology is rapid and ongoing. Far greater advances are being seen in the development of these methods than in conventional printing methods. For this reason, we will provide a more detailed overview of the technological improvements of digital printing methods. The evaluation of environmental performance will be an important part of the fast development of digital printing technologies. One of the advantages of digital printing is its masterless process, which yields several opportunities including faster makeready, less need of chemicals and lower waste output with the variable print data capabilities.

When the technologies were first introduced they were quite robust and the print quality was relatively low. The first development step was to improve print quality by increasing the resolution and adding process colours. The next development step is to make printing more economical by reducing energy consumption, lowering the cost of materials and extending the lifetime of the machine parts. The best results are achieved by developing the materials in tandem with the printing equipment. (Pira 2008.)

In electrophotography, several changes are made to improve print quality and at the same time reduce energy consumption. The manufacturing process of the toners has been changed from grinding the toner particles to the right size to chemically precipitating the toners to the right size. This processing leads to lower energy consumption and smaller toner particles with a smaller size distribution. The desired print density is achieved with a smaller amount of toner. The fixing of the toner to the substrate by heat and pressure also consumes energy, but the smaller particle size and thus thinner layer of toner reduces the energy need. Development of the toners to lower their fixing temperature has been possible by changing the wax and other materials in the toner. (Smyth 2008.)

The process of electrophotography has also developed in several ways. The changeover from lasers to LEDs in charging of the photoconductor drum has affected energy requirements and the lasers have also developed over the years. Using intermediate transfer of the toner from the photoconductor to the substrate extends the lifetime of the photoconductor drum and also allows the use of lower-quality substrates. (Smyth 2008.)

Transferring the toner from the drum or intermediate to the substrate uses a great deal of electricity. The development of toners and transferring coronas has reduced energy consumption because smaller amounts of material are now transferred with better technology. The charging power in the coronas is so high that ozone is developed. Reducing the amount of power needed also cuts down on ozone emissions. (Smyth 2008.)

Machine manufacturers recycle the containers of electrophotography materials and the used parts of the machine, but there is a lack of detailed information on how this is done.

In inkjet printing, development has mainly focused on printing heads and ink. The particle size in the pigmented inks has been reduced and thus the desired print density can be obtained with a smaller amount of ink. In dye-based inks, similar benefits have been obtained by the development of the dyes. This development has reduced the need for energy to dry the print. The share of UV printing will also continue to grow and the energy efficiency of the UV radiators, which can now be made with LED technology, is improving. Water-based inks are normally used in publication printing, but even when the ink is called water-based, it always contains solvent. The amount of solvents in the ink has now been reduced and the VOC emissions have also declined. (Pira 2008.)

Previously, the paper type was a dominant component influencing printing quality. Now, thanks to new printing technology, the first printing unit applies an invisible primer to the areas where ink will be printed, making the process less sensitive to the quality of the substrate. The primer can also be applied as a coating to the whole paper. The primer locks the ink to the top of the substrate and reduces penetration into the pores of the paper. In some applications the primer also facilitates the deinking of the print. (Pira 2008, Heilman 2009.)

The deinking of inkjet prints has been also discussed. The flotation process has been developed for traditional printing methods, such as offset. In inkjet, the small particle size of pigmented inks is problematic and dye-based inks can stain the pulp. The process needs to be modified to be suitable to the new technologies. Enzyme and biological removal of inkjet pigments and dyes already occurs. Technological development of inks has also influenced the deinkability of inkjet printing. Xerox has developed a solid ink method that is based on resin and has reached the grade “good” in INGEDE tests. Fujifilm applies a primer coating to the whole paper, which coagulates the pigments and makes the water-based inks hydrophobic, thereby improving deinkability. The Japanese company KAO has developed a method where the ink pigments are capsulated, which helps deinkability. (Pira 2008, Heilman 2009, Linna 2010.)

The move from thermal inkjet heads to piezo inkjet heads in the late 90s has certainly been a major driver of the current inkjet business. Now the new MEMS technology will reduce energy use even further. Variable dot sizes also influence energy needs. (Pira 2008, Heilman 2009, Linna 2010.)

It is hoped that in the future digital presses will also provide guidance to the operator about energy efficiency and the energy consumption data that can be allocated to specific products. To be able to calculate indicators such as the carbon footprint, printing houses need to systematically monitor resource usage. At this moment, obtaining product-specific material and energy flow data still seems to be a very laborious process. Special efforts and measurement settings were done to identify energy data needs (Haanpää 2010). Once measured, the studied printing house found several places for immediate savings of energy. Including such technology services in digital presses and devices will enable better and easier reporting of the environmental performance of products and improvement steps. Furthermore, any consumer questions in the field of environmental impacts can be addressed in a more manageable way.

3.3 Changes in environmental performance of printing

Due to the technology and work flow changes, the graphic arts industry has improved its environmental performance. The magnitude of the improvements is hard to measure but in the following chapters the areas of improvements are considered. The main focus of the analysis is on energy and material efficiency.

3.3.1 Energy efficiency

Based on the earlier studies and the data collected, the energy consumption of conventional printing houses has decreased considerably from the level of the early 1990s. That said, it must be noted that the situation can vary remarkably between different printing houses. Furthermore, care must be exercised in the interpretation of the results of different studies, as they are not totally comparable but rather indicative. One should notice that the energy consumption figures of the printing houses often include the total energy consumption of the production site and thus the type and size of the buildings can also affect the figures. Data from several printing houses is included in the studies in order to arrive at an understanding of typical consumption levels (Viluksela et al. 2008). Figure 6 presents a summary of the total energy consumption of different conventional printing methods with the updated data.

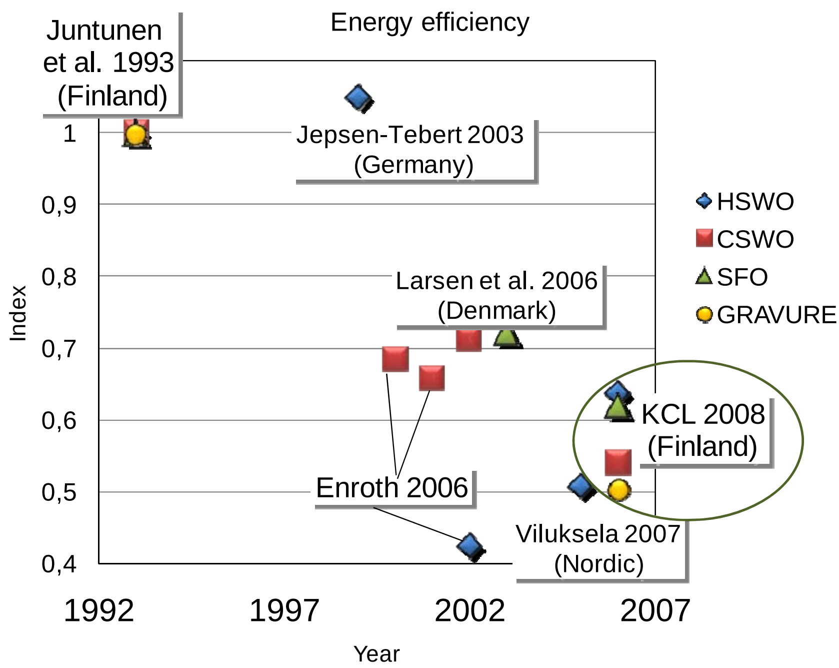


Figure 6. Energy consumption index of printing processes, calculated as total energy consumption per one tonne of printed products (Finnish ecobalance study from the year 1993 = 1), (Juntunen et al 1993 and Viluksela et al. 2008 with the updated data on gravure printing).

Although the downward trend in energy consumption is quite clear, there are differences between the results of the individual studies. This can be explained by differences in the timeframe, scope and geographical location of data collection, overall objective of the studies, number of companies involved, etc. The energy consumption levels are to some extent also dependent on the production structure and machinery. In addition, the energy consumption figures should be evaluated in relation to the infrastructure and production type. (Viluksela et al. 2008.)

Comprehensive studies concerning the indicator data of conventional printing are available in the literature, but no such studies were found concerning digital printing methods. The development trend in the energy consumption of electrophotography and inkjet printing was very roughly evaluated based on engineering theses, information from machine suppliers (web pages and questionnaire) and the literature found (Viluksela et al. 2010, Haanpää 2010, Hopponen 2010). Direct comparisons between machines and technologies are difficult because the data sources are not consistent and are partly based on manufacturer data. With these limitations in mind, one simple observation that can be made is that colour printing needs more energy than monochrome, which can be explained by the need for four colours instead of one to print and fix. A declining trend can be seen in the energy consumption of monochrome electrophotographic printing machines during the last 10 years, but for colour printing no clear trend was observed. (Viluksela et al. 2010.)

3.3.2 Material efficiency

The main material of fibre-based print products is paper. The study shows that paper consumption per one tonne of printed products in conventional printing methods like offset and gravure has either remained basically the same or shows a very slightly upward trend. The technical and process improvements in makeready and automated quality control should lead to more efficient paper utilization. On the other hand, shorter print runs, very tight schedules, the large scale of different types of materials and more complicated products (more colours, effects, paper grammages, etc.) may counteract these advantages. Since in many printed product groups, paper is the single most important factor both financially and ecologically, the efficient utilization of paper remains one of the challenges facing the printing industry (See Figure 7). (Viluksela et al. 2008.)

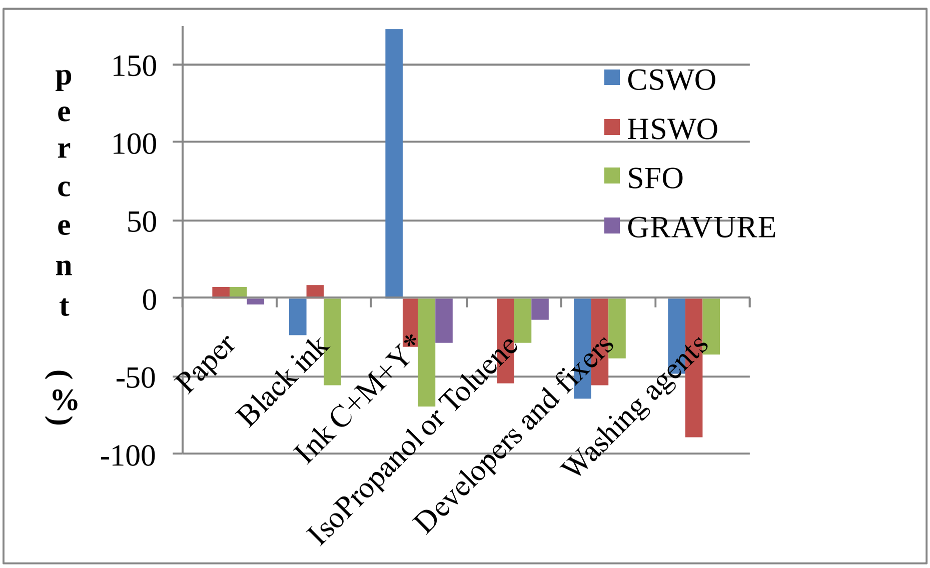


Figure 7. Relative change (per cent) in the use of paper, ink and some chemicals per one tonne of printed products in Finland, 1993–2007 (Reference year 1993 = 0). (Juntunen et al. 1994 and the updated research data).

The changes in ink consumption between 1993 and 2007 are interesting. In HSWO, the increase in black and decrease in coloured ink consumption per tonne of products could be explained by more effective under-colour removal or grey component replacement methods in colour separation. The notable increase in coloured CSWO ink consumption is due to an increase in four-colour printing of newspapers. In addition, the amount of colourëd advertisement leaflets has increased. The decrease in SFO ink consumption may be caused by the increased use of coated paper grades, which require less ink. (Viluksela et al. 2008) Equally the decreased need for ink in gravure may be due to improved SC paper quality and enhanced paper qualities. Also, ink formulations have been improved. (See Figure 7.)

The consumption of other materials has generally decreased since 1993. Isopropanol, one of the causes of VOC emissions, is being replaced or phased out (Viluksela et al. 2008). Furthermore, toluene consumption has declined thanks to more efficient recovery of toluene.

The use of fixing agents has decreased in offset due to the changeover from films containing silver – which were categorized as hazardous waste – to digital prepress, CTP plates and the recently introduced chemistry-free and processless plates. The consumption of washing agents has decreased with the growing use of automatic blanket washing devices. (Viluksela et al. 2008.)

The output of different waste fractions mainly describes materials and process efficiency as well as waste sorting. Stricter legislation and higher waste handling and processing costs have boosted improvements in waste sorting and recovery. (Viluksela et al. 2008.) The indicative change concerning waste handling is presented in the following diagrams, which are based on Juntunen et al. 1994, the gathered research data (from 2006–2007) and the article published in 2002 based on a study by Pöyry Consulting. (See Figure 8.)

When analyzing the waste output data, comparing the figures with different studies is somewhat complex because the sorting of different waste fractions can vary depending on the local waste infrastructure. In particular, if one is looking at studies conducted in different countries. There may even be some differences in waste sorting between different municipalities within a country. However, on a general level, the results related to the amount of waste (per tonne of printed products) indicate positive development and improvements in waste sorting. The most positive and important indication is the decrease in the amount of landfill waste.

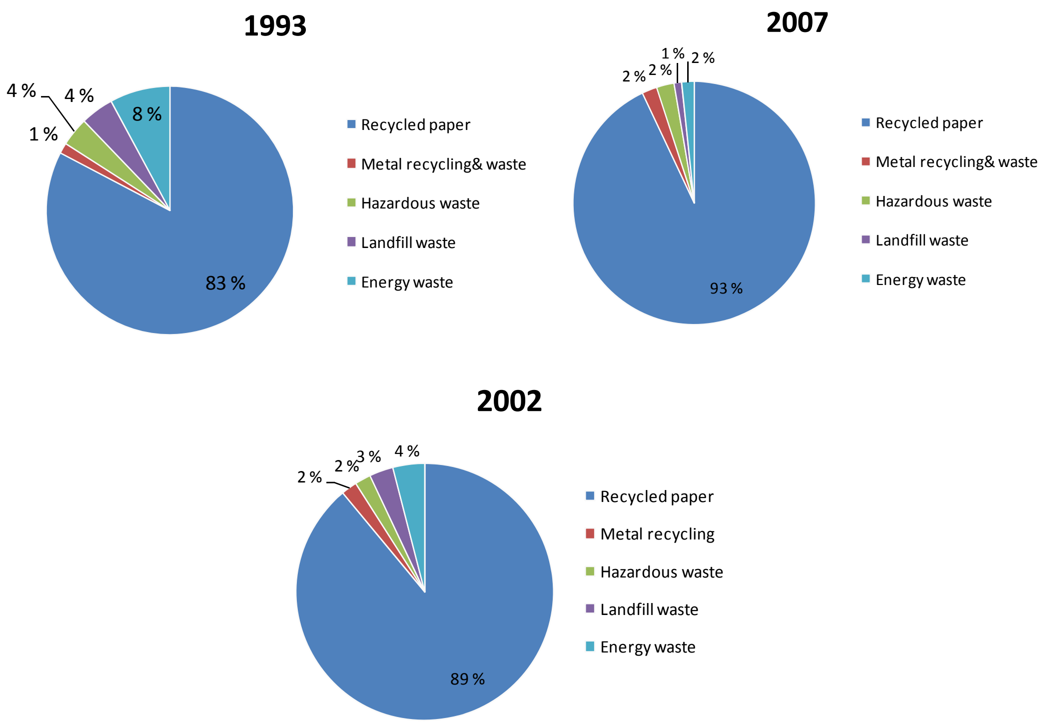


Figure 8. Distribution of waste (w%) in Finland. On top are conventional printing plants (HSWO, CSWO, SFO, Gravure) (Juntunen et al. 1994) and research data (2006–2007). Finnish printing houses are shown below (Painomaailma 7/2002). Results are indicative, not directly comparable.

3.4 Conclusions and discussion

With the help of indicators, a printing house can follow the key figures for its production in respect of environmental performance. The challenge is to have accurate figures that are allocated to a specific print product group or product. This effort is laborious but rewarding and vital. In addition, indicator information helps one pinpoint where environmental performance can be enhanced. Furthermore, with the help of precise information, it is possible to calculate and systematically follow indicators such as the carbon footprint. This makes it possible to provide environmental information about print products to different interest groups. There is a growing need for communication in internal operations, B-to-B and consumer relationships.

Chapter 3.1.1 presented a table of indicators for printing based on data collected from the years 2006–2009. The values in the table give indication of the magnitude, but they cannot be used to compare different printing methods because the products and their volumes (high volume production/low volume production) are different. Furthermore, some of the figures are estimates, which also brings in variation. In addition, the technology and materials differ significantly between the methods.

The study "Changes in sustainability due to technology development in selected printing processes" (Viluksela et al. 2008) made in the early stage of this project – pointed out that the relationship between the LCI data, sustainability performance and technological developments is multidimensional, and the impacts are not always clear. To really understand the overall environmental impacts of the print products and to identify the most critical factors, it seems to be important to cover the whole production chain and the life cycle from the forest until the end of life (recycling, incineration or disposal to landfill).

The results presented in this chapter, including the updated indicator information, can be regarded as the indicative and relative research results for environmental sustainability and technology development in a 15-year timeframe. New data gathering and evaluation of environmental indicators for printing made it possible to calculate several life cycle assessments and carbon footprint case studies for different printed products. These case studies are presented in Chapters 5–9.

We also found out that there is still a lack of systematic devices or displays that give detailed information about energy consumption in the printing houses. It would be very helpful to have a reporting system that facilitates the monitoring of the energy and material consumption of production and allocates it to specific product types. For instance, the manufacturer could include such functionalities in the press. Furthermore, such a system could enable the identification of the differences between print products (which vary in size, in quality, in complexity, in volume) in respect of environmental performance.

For all the abovementioned reasons, it is important to keep track of the detailed amounts of products and by-products, materials, different waste fractions (maculature, renewable, reusable and non-renewable materials) as well as the energy consumption figures. To conclude, the importance of evaluating environmental performance is clear together with the development of technology and workflows to achieve empowered sustainability. Regardless of how new and novel the technology in use at printing house is, the operating and manufacturing procedures have an effect too. Furthermore, accurate information about energy and material flows plays a key role on the road to improved environmental performance.

4. Assumptions related to case studies

The following chapter describes some basic assumptions and system boundaries common to all the case studies. Firstly, the life cycle stages included in the case studies are presented and secondly, assumptions related to transport and product end of life are discussed. In addition, the principles of allocation are discussed. Detailed descriptions of system boundaries and case-specific assumptions are presented in the context of each case study.

4.1 Background and general assumptions

The case studies cover the life cycle of print products from cradle to grave: pulp and paper manufacturing (including harvesting and raw material manufacturing), print manufacturing, distribution of final products from the printing house to the consumer (home delivery), transport related to paper and waste collection, paper recycling, incineration and disposal to landfill. A cradle-to-customer study was carried out for a photobook and a cradle-to-retailer study was done for a book; end of life was excluded from the examination. Infrastructure (buildings, machinery, and other devices) and supporting functions like sales and marketing, etc. are not included in the calculations. Editorial work related to newspaper and magazine production is not included. Transport covers the manufacture of the main raw materials and products and the end of life phase.

Table 5. Description of main processes included in different life cycle stages.

Life cycle stage	More detailed	Included processes
Fibre supply	Fibre supply	Harvesting, sawmills, fuel and energy supply in harvesting and sawmills
Pulp and paper mill	Direct emissions from pulp and paper mills	Direct emissions from pulp and paper mill sites
	Purchased electricity at pulp and paper mills	Production of grid electricity
	Chemicals, materials and fuels at pulp and paper mills	Manufacturing of pulp and paper chemicals, raw materi-als (other than wood) and fuels
Printing	Direct emissions from printing	Direct emissions from printing sites
	Purchased electricity at printing houses	Production of grid electricity
	Chemicals, materials and fuels used in printing	Manufacturing of printing ink, printing plates, other fuels and materials (e.g. glues) needed in printing
Delivery to customer or end user	Delivery to customer or end user	Distribution of magazines, newspapers, advertisements and photobooks to consum-ers (home delivery) or trans-portation of books to retailer's warehouse
Other transportation	Other transportation	Wood, chemical, fuel, other raw material and waste trans-portation
End of life	Processes related to prod-uct end of life	Energy needed in recycling, processing of collected paper, landfill emissions, emissions from energy recovery
Avoided emissions	Avoided emissions due to, e.g. recycling or combustion	Avoided processes and en-ergy production, specified separately in each case

4.1.1 Fibre supply

Carbon sequestration in forests was excluded from the case studies due to the lack of a justified methodology to determine the precise effect of an individual product on forest carbon (see also Chapter 2.2). Thus, fibre supply includes the emissions from harvesting operations in the forest.

4.1.2 Emissions from pulp and paper mills and printing houses

In the case studies, the direct emissions from pulp and paper mills and printing plants include, for example, emissions from fossil fuel combustion on site. Production of purchased electricity consumed by the mills and printing plants contributes to emissions as well and is reported separately in each case. Electricity production modules used in the study are presented in more detail in Appendix C. The emissions from raw material manufacturing are reported separately.

4.1.3 Transportation in the study

Transportation of raw materials and products was included, covering the whole life cycle of the product from cradle to grave. Emissions from transport were calculated on the basis of mass (as tonne-kilometres) using information acquired from the KCL EcoData database, the Finnish Environment Institute (SYKE), a paper recycling company and a Finnish logistics company. Delivery to customer is derived from a Finnish logistics company and the data represents the emissions generated by the delivery of each printed product. Other transportation distances and modes of transport are estimates but they reflect common situations in Finland. In the gravure-printed case a scenario analysis was undertaken for transport between Europe and Finland. These assumptions for transportation distances in Europe are presented in detail in Chapter 8. Assumptions related to distances and modes of transport in Finland are presented inTable 6.

Table 6. Transportation in the study.

Raw material	Mode of transportation	Distance [km]
Wood	Truck 42 t	90
Chemicals	Truck 25 t	200
Printing ink	Truck 25 t	200
Printing plates	Truck 25 t	200
Paper to printing plant (newspaper, magazine, photobook, gravure, book*)	Truck 25 t	200 *book 400 km
Delivery to customer	Data on emissions sourced from a Finnish logistics company	
End-of-life transportation	Truck 25 t	50

Back haulages were included, assuming that after transporting the product, the vehicle drives half of the distance with an empty load.

4.1.4 Assumptions concerning product end of life

Landfill

Different end-of-life options and their effect on climate change have become increasingly important in product-specific LCAs and therefore special attention should be paid to how the emissions from landfill and other end-use options are included in an LCA.

A commonly referred greenhouse gas inventory produced by the IPCC provides estimations and recommendations on how the methane production and release from paper degradation in landfills should be calculated. The greenhouse gas inventories produced by the IPCC only look at fossil CO_2 emissions and do not include the calculation of carbon sinks or biogenic carbon. This has raised debate on how to deal with, for example, carbon being stored in landfills and carbon of biological origin. This is important for wood-based products.

Various researchers have argued that the current estimations given, for example, in the IPCC recommendations for methane production and release from paper disposed to landfill are over-estimations (Barlaz 2006; Ximenez et al. 2008) However, there is currently insufficient field evidence to determine what proportion of carbon from forest products potentially lost through degradation is emitted as carbon dioxide and methane. One updated calculation of the carbon content of newsprint and its methane production potential has been developed by the Technical University of Denmark (DTU), which carried out an LCA on waste management systems.

To find out the importance of landfill characteristics and assumptions, two different landfill modules were used in the study. One landfill module was formed according to the greenhouse gas inventory provided for IPCC (later LF high). In addition, another landfill module was created according to the model developed by the DTU. This module is called LF low in the study, because it is assumed that landfill gases are collected efficiently and paper decays slowly at the landfill, and that thus its emissions are remarkably lower than those of the landfill assessed with IPCC default values. Landfill characteristics for both studied landfills are presented in Appendix I.

The basic assumption in the landfill calculations was that 50% or less of the degradable organic carbon in landfills decomposes to carbon dioxide and methane. Lignin, one component of newsprint, may stay in the ground for several decades or even centuries and, according to Barlaz (2006), may prevent even other compounds from degrading. Collected landfill gas is assumed to be burned either in a flare or microturbine; the shares of the combustion technologies are 44% to 56%, respectively (Mattila et al. 2009). When landfill gas is burned in a flare, energy cannot be recovered but methane is converted to carbon dioxide, thereby reducing climate impacts. It was assumed that 56% of the landfill gas is burned in a microturbine. A microturbine produces both electricity and heat, and its total efficiency is 83% (Manfredi et al. 2009). Microturbine parameters are presented in Appendix K.

The comparison of two different landfill modules for paper waste landfilling gives the range of the climate change impacts of newspaper waste in landfills. In Finland the landfill gas collection rate at different sites varies from 50% to 70%, but the overall collection rate is 50%, which is lower than in both of the landfill modules used for the newspaper scenarios. However, in both modules the share of degradable organic carbon is 40%, of which 50% is assumed to dissimilate in LF high and 16% in LF low. Lignin in newsprint degrades slowly, so the impacts of methane emissions from newspaper waste landfilling at the Finnish landfills are somewhere in between the results of the two scenarios. It should be noted that the LF low landfill module was prepared for newsprint and thus uncertainty related to landfill emissions might increase to some extent when applied for other paper grades. In this study, the LF low newsprint landfill module is applied to other paper grades as well due to lack of data. The greenhouse gas inventory data provided by IPCC is applicable to any paper grade.

Treatment of recycled fibre

After a fibre-based printed product is used, it can be recycled. Maculature from printing is also recycled and used as a raw material in either paper manufacturing or other industrial processes. It can be assumed that recyclable fibre is a co-product of the system and a methodological choice must be made on who gains the benefits of recycling. There are several ways of treating the recycled fibre and allocating the environmental load of manufacturing to that part of the fibre that can be reused again (see also Chapter 4.1.5). In this research project, different methodological choices have been studied in order to examine the effect and benefits of recycling and the impact of the different allocation methods on the results. Different methods are applied in different cases and these methods are specified in the case definitions.

Avoided emissions

When modelling the life cycle of a printed product, it can be seen that a printed product is not the only outcome of the studied system. As mentioned before, the studied system produces recyclable fibre. In addition, printed products can be combusted in a waste incineration plant in which the energy content of a product is utilized and the energy is recovered, producing both electricity and heat. Electricity and heat are also produced in landfill microturbines. If it is assumed that the studied system produces not only printed products, but also recycled fibre and energy, benefits can be calculated for the system. A transparent way of calculating the benefits is avoided emissions. In this study, avoided emissions are emissions that are avoided either by replacing primary fibre in paper production or by replacing average electricity or heat production. Avoided emissions are defined in greater detail in each case and reported separately. Depending on, for instance, what kind of electricity is assumed to be replaced, the impact of avoided emissions might be significant.

4.1.5 Allocation

Allocation means partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (ISO 14040-44). Allocation is necessary when a product system produces several products. In addition to the by-products of manufacturing processes, allocation also applies to reuse and recycling situations. When several products or recyclable materials are produced in the product system and are used in other systems (e.g. recycled fibre is used to produce another fibre product), it is justified to share the environmental burdens between these products and product systems.

There are different ways to carry out an allocation. ISO 14040-44 standards give guidelines on what principles the choice of allocation should be based on. However, there is room for interpretation and thus it is important that the allocations made in the study are reported transparently and, if several alternative allocation procedures seem suitable, a sensitivity analysis should be made.

Depending on the context, different allocation methods have been applied in the case studies. The principles of the used allocation methods are described in the case definitions.

5. Life cycle assessment and carbon footprint of a coldset offset printed newspaper

This chapter presents the results of an LCA case study and carbon footprint calculation for a coldset offset printed newspaper. It is assumed that the product is manufactured and read in Finland. In 2008, the circulation of newspapers was around 3.1 million in Finland, of which two-thirds (2/3) were daily newspapers. Around 200 different newspapers were published. The amount of time Finnish readers dedicated to the reading of newspapers in 2007 was roughly 34 minutes per day. (VKL 2009, Statistics Finland 2008) On average a Finnish person reads (follows) two newspapers (KMT 2009). The majority of newspapers, roughly 69%, are delivered to homes at night or in the early morning. The rest of the newspapers are delivered in the daytime (18%) or bought from shops (13%). (VKL 2009, Statistics Finland 2008.)

Coldset offset printing is used for the economical production of newspapers and catalogues. It is a process that employs fast presses with typical web widths of 0.6 to 2 meters. Newspaper printing is local business with tight time table and therefore there are many coldset printing houses. In each printing house several printing webs are printed simultaneously and the webs are combined to form the final product. Typical print runs are between 15 000 and 250 000 copies.

Offset lithography is a complex printing process in which the printing plate is divided into chemically differing image and non-image areas, where the difference is induced by photochemical reaction. In the printing process, the plate is first dampened with a fountain solution, which adheres to the non-image areas of the plate. In the following stage, nip ink rollers apply ink only to the image areas of the printing plate. The image on the plate is transferred via a rubber blanket to the substrate under nip pressure.

Inks used in coldset offset are mineral or vegetable oil-based and they do not dry, but rather set to the paper. The aluminium-based printing plates and maculature are recycled.

Newsprint is a short lifespan paper with high bulk and good opacity. The paper is made by using machine calendering without other surface treatment. It has traditionally been produced from mechanical pulp, but nowadays it is increasingly made from deinked pulp. Deinked pulp (DIP) is produced from recycled paper and the printing ink is separated from fibres by means of a flotation process. Thermomechanical pulp (TMP) is made from wood chips that are treated in a TMP refiner, applying pressure and heat to separate the fibres. TMP also contains lignin from the wood. Fillers in newspaper are mainly clay and calcium carbonate ($CaCO_3$) and their ratio depends on the paper manufacturer and the quality of recycled paper.

5.1 Case definition

The goal of the case study was to examine the potential environmental impacts of a Finnish regional newspaper. Different scenarios were studied to evaluate the possible variations in the results. The case study does not present any specific newspaper manufactured in Finland, but rather a possible value chain for the manufacturing and use of newspaper. The basic parameters and assumptions were defined together with representatives of the paper and printing industry.

The functional unit used in the study was 1000 kg of newspapers. Additionally, carbon footprints were calculated for one newspaper and for a yearly subscription of newspapers based on the assumed weight of the product. The scope of the study was cradle to grave, which means it covered the whole life cycle of a newspaper, from raw material manufacturing until the disposal of the read newspaper.

Table 7. Case study assumptions for a CSWO printed newspaper.

Print product	Newspaper, approx. 48 pages (broadsheet)
Printing	Coldset web offset (CSWO), 4-colour printed
Paper	40 gsm newsprint 60% DIP, 35% TMP, 5% fillers
Circulation	Less than 80 000
Yearly subscription	356 issues
Weight and dryness	200 g/piece, 88%
Geographical aspects	Paper production, printing, delivery and disposal in Finland
Distribution	Direct to home at night
End-use of product	Recycling 79% Landfill 16% Incineration 5%

Figure 9 shows the system boundary of the studied system with wood fibre flows (moist). The main steps of the life cycle are raw material acquisition, energy production, paper manufacturing, printing, product delivery to consumers and treatment of the waste paper after disposal. Newspaper editorial work was not included in the study. It was assumed that the newsprint used for newspaper is manufactured partly from deinked pulp (60%) and partly from thermomechanical pulp (TMP) (35%); the remaining 5% consists of fillers. The paper is manufactured in Finland. Data on paper manufacturing was derived from a Finnish newsprint manufacturer and combined with the data from the KCL Ecodata database, and data on printing was collected from Finnish printing houses. The used maculature percentage for printing was 14%.

For production of grid electricity and heat, a five-year Finnish average was used. The electricity and heat production mixes are presented in Appendix C. Data on printing ink was derived from the Ecoinvent database, representing average data on offset printing ink. The offset printing ink used in the study contains both mineral and vegetable oil. Data on printing plates is based on Life Cycle Inventory data from the European Aluminium Association (EAA 2008) and the recycling of aluminium plates was included in the study. Data sources and data age are presented in detail in Appendix F.

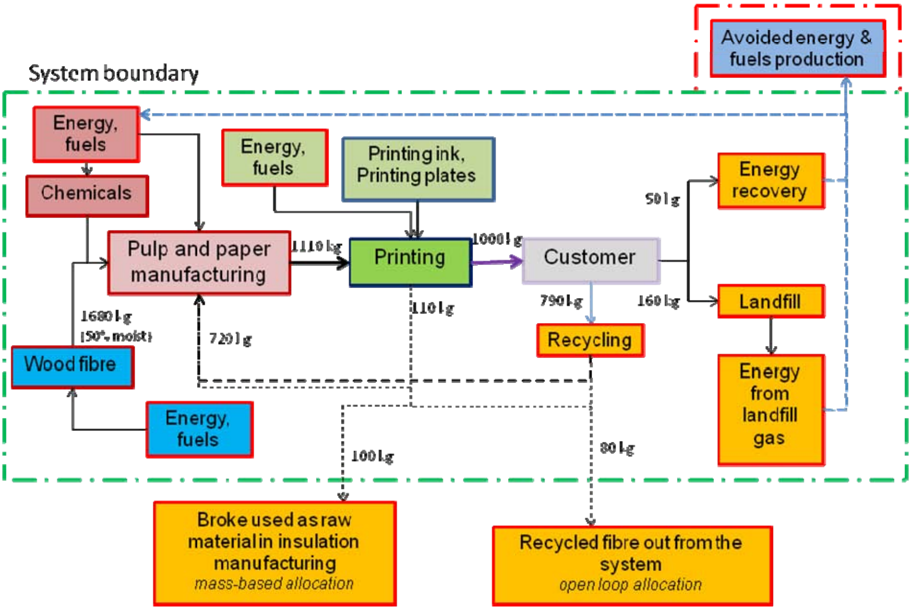


Figure 9. System boundary of the studied newspaper with wood fibre flow (moist).

In order to find out the significance of the made assumptions, several scenarios and sensitivity analyses were calculated for newspaper. As mentioned before (see Chapter 4.1.4), the decay rates in landfills are uncertain and both the amounts of landfill gas collected and the efficiency of collection systems vary, and therefore two different landfill options are studied.

In the basic case, the production of grid electricity is based on the five-year Finnish average, in which 43% is produced using fossil sources and 28% using nuclear power. In the future, the intention is to produce more electricity with renewable energy resources. In this study, the impact of replacing the average grid electricity with renewable electricity was studied in a green electricity scenario. In the scenario, it is assumed that all the purchased electricity in the system (raw material manufacturing, pulp and paper mills, printing plants) is produced with renewable resources. However, some of the used modules (printing ink and printing plate manufacturing) are aggregated LCI modules and the data on purchased electricity could not be separated from the modules. Because paper mills and printing plants are the major electricity purchasers in the value chain and thus the error caused by not changing the electricity production mix in printing ink and printing plate manufacturing is not notable in the green electricity scenarios. The production mix of renewable electricity was based on Finnish energy statistics (IEA 2008). The used production mix for green electricity is: ~58% hydropower, ~41% biomass and ~1% windpower.

The assumptions concerning end-of-life shares are based on the data collected from a Finnish paper recycling company. In general, the paper-recycling rate in Finland is very high, but it is estimated that a small amount of newspapers is still disposed of in landfills or combusted. Because the assumptions made concerning the end-of-life shares have a clear impact on the carbon footprint results, several hypothetical end-of-life scenarios were calculated as well. Therefore the carbon footprints for the maximum scenarios of 100% recycling, 100% to landfill and 100% to energy recovery were studied.

Table 8. Studied scenarios in the newspaper case. Basic case highlighted with orange.

<table>
<tr><th>Case</th><th>Landfill option</th><th>Electricity</th><th>End-of-life treatment</th></tr>
<tr><td>LF high,
basic case</td><td>High</td><td rowspan="2">5-year average Finnish grid electricity</td><td rowspan="4">79% recycling
16% landfill
5% incineration</td></tr>
<tr><td>LF low</td><td>Low</td></tr>
<tr><td>LF high, green</td><td>High</td><td rowspan="2">Green electricity</td></tr>
<tr><td>LF low, green</td><td>Low</td></tr>
<tr><td>LF high,
100% recycling</td><td>-</td><td rowspan="3">5-year average Finnish grid electricity</td><td>100% to recycling</td></tr>
<tr><td>LF high,
100% incineration</td><td>-</td><td>100% to energy recovery</td></tr>
<tr><td>LF high,
100% landfill</td><td>High</td><td>100 % disposed to landfill</td></tr>
</table>

Life cycle impact assessment was conducted for both landfill scenarios (LF high and LF low) (See chapter 4.1.4) and for the green electricity scenario. For the 100% end-of-life scenarios, only the carbon footprint was studied.

5.2 Allocation procedures

Different allocation methods have been applied when modelling the life cycle of newspaper. Maculature created in the printing house and post-consumer fibres can be recycled and reused again. There are several methodological options for treating the recycled fibre that is produced in the system. The allocations are explained in the following subchapters.

5.2.1 Allocation in the printing house

When a production process produces more than one product and the products can be assumed to be somewhat equal in value, mass-based allocation can be carried out. In newspaper printing, the amount of maculature created as a side product is about 114 kg (per tonne of newspapers) and it was assumed that 100 kg of that is sold to insulation manufacturers and this amount was allocated by mass. Not all the maculature is used in insulation material and thus the rest (14 kg) is assumed to be recycled in paper recycling. Allocation in the printing house is presented in Table 9.

Table 9. Allocation in the printing house.

	Mass [t]	Allocation factor
Printed newspaper	1000	0.91
Maculature used in insulation material manufacturing	100	0.09
Maculature to paper recycling	14	Used in the system

5.2.2 Allocation of printing plates

Printing plates in newspaper manufacturing are manufactured from primary aluminium. Data on aluminium is based on the LCA study of the European Aluminum Association (EAA 2008) and the data received from the EAA. Printing plates are manufactured 100% from primary aluminium. Printing houses recycle the plates very efficiently. In this study, it was assumed that 97% of printing plates are recycled and the loss in the recycling process is about 0.7%. Open-loop allocations were used because the further use of recycled printing plates was not known exactly. The principles of open-loop allocations are presented in Appendix G. Open-loop allocation gave an allocation factor of 13.6% for the primary aluminium, and the rest (86.4%) of the inputs and outputs are allocated to the recycled printing plates. The allocation percentage for recycled aluminium is rather high due to the high recycling rates and good recyclability of aluminium.

In general, aluminium enjoys high recycling rates at the European level, e.g. approximately 90–95% for transport and construction applications. Comprehensive systems for the recovery of used aluminium now exist in all major European countries (EAA 2007). In Finland, Kuusakoski Oy has manufacturing facilities for secondary aluminium ingots. They are tailor-made for customers from recycled metals. The main utilization areas are the automotive and electronics industries. Offset printing plates are good raw material for ingots because of their low-alloy properties. Partly, the offset plates are delivered directly to industry in Finland and abroad for use as raw material. (Kuusakoski Oy 2010.)

5.2.3 Allocation of recycled fibre

In the study, it was assumed that 79% of newspapers are recycled after use. As Figure 9 shows, recycled fibre can be used again in the system because the studied newsprint is manufactured partly from recycled fibre. The studied system produces 80 kg more recycled fibre than it uses and therefore a small proportion (~4%) is allocated out of the studied system by open-loop allocation. The principles of open-loop allocation can be found in Appendix G.

5.2.4 Energy produced in the system

Newspaper is recycled, disposed to landfill or disposed to energy waste after being read by consumers. As a newspaper decays in a landfill, it produces landfill gas – this gas can be collected and burned in a flare without energy recovery or its energy content can be utilized. As previously mentioned in Chapter 4.1.4, it was assumed that landfill gas is combusted in a microturbine that produces heat and electricity. In addition to landfilled newspaper, a small proportion of newspapers end up in waste incineration plants that produce heat and electricity. All of the produced electricity is utilized in the studied system. When it comes to heat, the system uses less auxiliary heat than it produces and therefore it was assumed that the produced heat replaces average Finnish heat production (system expansion).

5.3 Life cycle inventory results

The life cycle inventory results presented in this chapter include emissions to air (NOx, SO_2, TSP and VOC) and emissions to water (COD, Ntot, Ptot, TSS). All greenhouse gas emissions are reported separately in Chapter 5.4 Carbon footprint results. The aspects related to solid waste are discussed but not reported in detail due to high uncertainty concerning the used background data on solid waste amounts. All LCI results for different scenarios are presented in detail in Appendix E.

5.3.1 Emissions to air

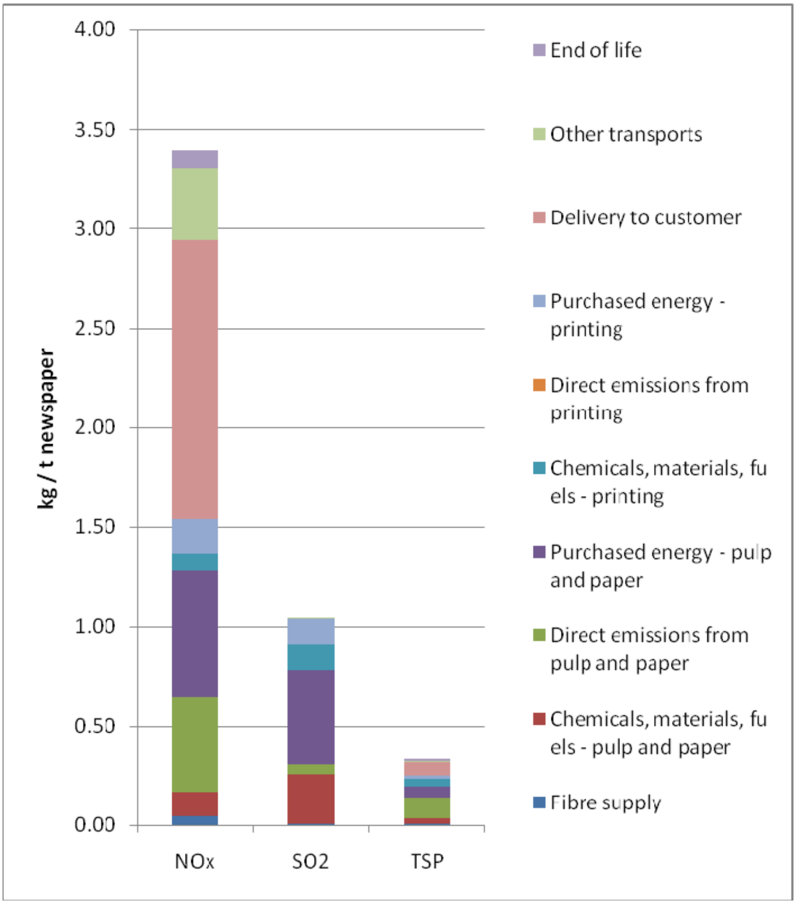


Figure 10. NOx, SO_2 and TSP emissions to air during the life cycle of newspaper in the basic case [kg/tonne of newspaper (air dry tonne)].

Figure 10 presents the following emissions to air: nitrogen oxides (NOx), sulphur dioxide (SO_2) and total particulate matter (TSP). (For GHG emissions, see Chapter 5.4.) NOx and SO_2 emissions contribute to acidification and particle emissions can cause respiratory diseases.

Based on the LCI results, the delivery of newspapers to consumers has the biggest contribution (41%) to NOx emissions. Other significant sources of NOx emissions are the production of purchased energy for pulp and paper making (19%), pulp and paper manufacturing (direct emissions 14%) and other transport during the life cycle of newspaper (11%). TSP emissions originate mainly from pulp and paper mills (32%), the production of purchased energy for pulp and paper making (18%) and the production of chemicals, materials and fuels for printing (12%). Home delivery creates 21% of all TSP emissions.

The largest share of the SO_2 emissions (45%) are related to the production of grid electricity and heat used in the pulp and paper manufacturing phase. Other sources of SO_2 are the production of chemicals, materials and fuels for pulp and paper-making (24%) and for printing (12.5%). Production of purchased energy for printing houses creates 12.5% of the sulphur dioxide emissions. The entire paper manufacturing phase (incl. fibre supply, direct emissions from pulp and paper mills, raw material manufacturing and production of purchased electricity) is clearly the biggest contributor of SO_2 and TSP emissions. The entire printing phase (incl. chemicals, materials and fuels needed in printing and purchased electricity) contributes about 8% of total NOx emissions, about 25% of SO_2 emissions and about 15% of total TSP emissions. There are no direct NO_x, SO_2 or TSP emissions from printing houses.

VOC emissions in the basic case are presented in Figure 11. It can be seen that most of the VOC emissions come from printing house (~64%). In addition, some VOC emissions are emitted when chemicals (printing ink) and fuels (natural gas) are manufactured for printing and pulp and paper making purposes. Other life cycle stages have a minor or no contribution to VOC emissions. The variation in VOC emissions is negligible between the studied scenarios and therefore the emissions for different scenarios are not reported.

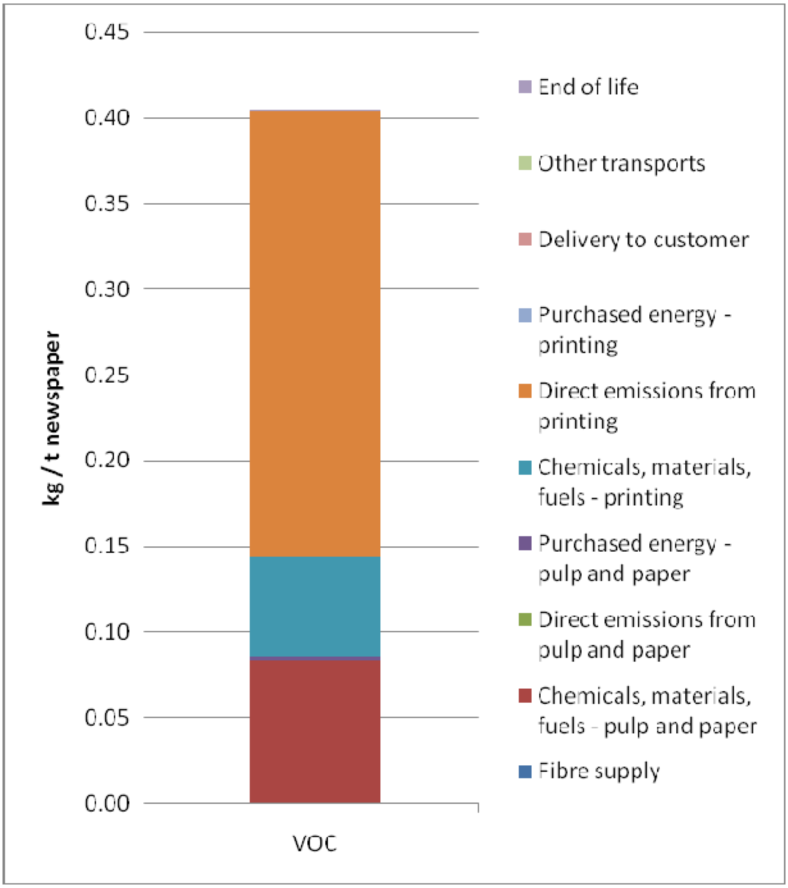
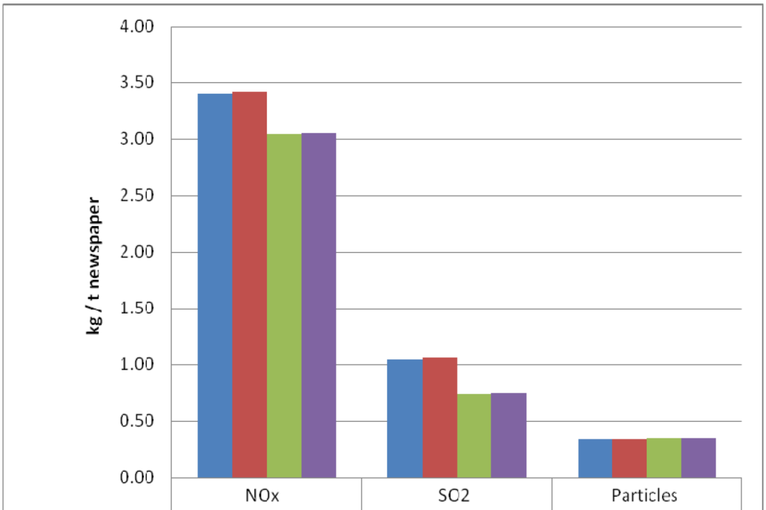


Figure 11. VOC emissions emitted during the life cycle of a tonne of newspapers in the basic case [kg/tonne of newspapers (air dry tonne)].

As presented in Table 8, different scenarios were calculated for newspaper. The sensitivity of landfill characteristics was studied due to the high uncertainty of the landfill assumptions (see Chapter 4). The effect of choosing greener electricity was also studied. In the green electricity scenario, all the purchased electricity was assumed to be produced with renewable energy sources (biomass, hydro and wind, reported in detail in Chapter 5.1). Figure 12 shows the variation in emissions to air when landfill characteristics change and when electricity is replaced with renewable electricity.



	NOx	SO2	Particles
LF high	3.40	1.04	0.34
LF low	3.42	1.06	0.34
LF high, green	3.04	0.74	0.35
LF low, green	3.05	0.75	0.35

Figure 12. NOx, SO_2 and TSP (particles) emissions to air during the lifecycle of newspaper with different landfill and electricity assumptions. [kg/tonne of newspapers (air dry tonne)].

5.3.2 Emissions to water

Chemical oxygen demand (COD), total nitrogen (Ntot), total phosphorus (Ptot), total suspended solids (TSS) and adsorbable organic halogen compounds (AOX) were included in the inventory (Table 10). The COD figure expresses the amount of organic oxygen-consuming compounds in the wastewater. AOX expresses the amount of chlorine contained in the organic compounds. When released to the water system, nitrogen and phosphorous emissions cause eutrophication. TSS means the amount of solid matter included in the wastewaters.

In the case study, pulp and paper mills are the biggest contributor to studied water emissions. Majority of the COD emissions (95%) and TSP emissions (94%) originate from pulp and paper mills. In addition, 50% of total nitrogen and 84% of total phosphorous emissions are related to the pulp and paper manufacturing phase. At paper mills, wastewaters are purified before being released into the water system and nitrogen and phosphorous are applied in the water purification process. TSS from pulp and paper making can include, for example, bark components and fibre fragments. However, the levels of water emissions from pulp and paper making in the LCI are mostly within the limits defined in the reference document on the Best Available Techniques in the Pulp and Paper Industry (BREF) (EIPPCB 2001). Only the COD and TSS emissions are slightly above the limits of the BREF document.

Another contributor to water emissions is vegetable oil-based printing ink manufacturing. The printing phase as a whole (incl. chemicals, materials and fuels needed in printing and purchased electricity) has an overall contribution of 5% to COD emissions, 46% to Ntot emissions (nitrate emissions from manufacturing of printing ink), 15% to Ptot emissions (phosphate emissions from manufacturing of printing ink) and 4% to total TSS emissions. There are no direct emissions to water from printing houses. The small amount of AOX emissions originates from printing ink manufacturing and refining of natural gas used for energy production. The variation in the amounts of emissions to water between the studied scenarios is negligible.

Table 10. Emissions to water during the life cycle of a newspaper in the basic case [kg/tonne of newspapers].

Emissions	Newspaper life cycle	
COD	5.04	kg
Ntot	0.16	kg
Ptot	0.006	kg
TSS	0.854	kg
AOX	0.0025	g

5.3.3 Solid waste

When cradle-to-grave solid waste amounts are calculated (but consumer waste is excluded), about 345 kg solid waste is produced/tonne of newspapers. 14 kg of the amount is maculature from the printing house and goes to paper recycling. 100 kg of maculature is considered to be a side product and allocated out of the syste. Therefore it is not included in the solid waste numbers.

Solid waste is mostly recyclable or combustable, but a small amount of hazardous waste is also produced. The amount of hazardous waste equals 1.1% of the total waste amounts. Hazardous waste from printing houses can typically include cleaning rags and some ink waste, for example. Landfill waste from paper manufacturing can include ash and some deinking waste. In general, the recycling rates of different waste fractions in both the paper and printing industries in Finland are high (see, e.g. Finnish Forest Industries Federation 2009b; Viluksela et al. 2008).

However, the amounts of solid waste contain considerable uncertainty because the completeness of data related to solid waste along the newspaper value chain is poor and therefore the amounts of solid waste are not reported in more detail.

5.4 Carbon footprint results

The carbon footprint includes the greenhouse gas emissions produced during the entire life cycle of products (for more information see Chapter 2.2). The (cradle to grave) carbon footprint of newspaper in the basic case is 1066 kg CO_2eq/tonne of newspapers. The result is presented in Figure 13. In the basic case, a landfill module with higher landfill gas emissions was used and therefore the landfill emissions make a big contribution to the overall carbon footprint.

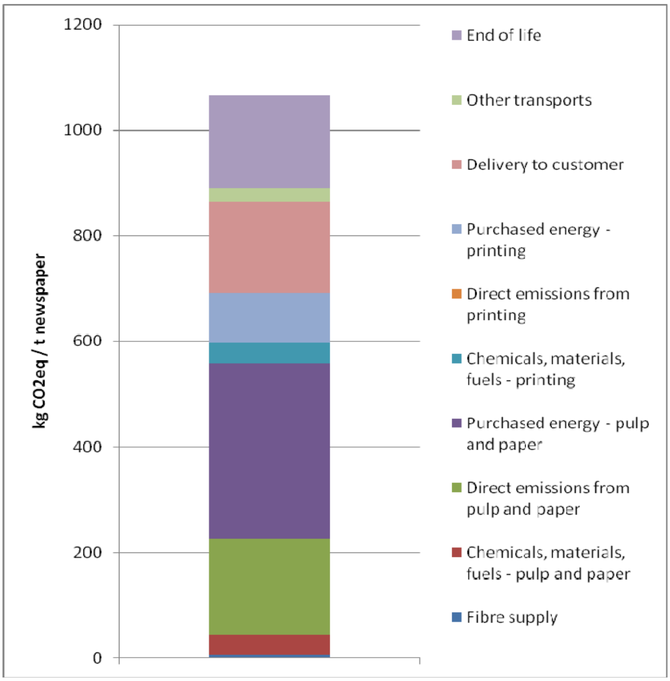


Figure 13. Carbon footprint in the basic case is 1066 kg CO_2eq/tonne of newspapers (air dry tonne).

The carbon footprint of a newspaper is divided into life cycle stages. The following figure (Figure 14) shows the contribution of each life cycle stage to the carbon footprint. It can be seen that more than one fourth of the emissions come from the production of the purchased electricity used by paper mills. Fossil fuel combustion at pulp and paper mills contributes 17% to total greenhouse gas emissions. Delivery to customer has a large contribution to the total carbon footprint, accounting for about 16% of the total greenhouse gas emissions. Additionally, emissions from landfills have a big impact on the carbon footprint of a newspaper. The results (including the cradle to gate results) are presented with more detail in Appendix E.

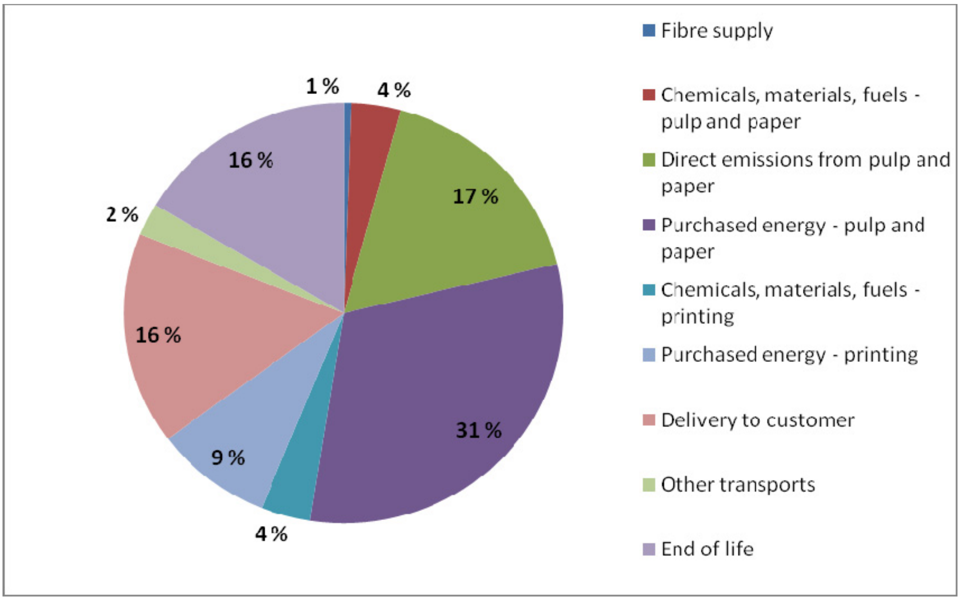


Figure 14. Carbon footprint of a tonne of newspapers in the basic case, divided into life cycle stages.

Even though only a small amount of newspapers (17%) is disposed to landfill, the emissions from landfills make a big contribution to the carbon footprint. Therefore the sensitivity of landfill emissions was studied with two different landfill modules. Based on the life cycle inventory results, the carbon footprint for one tonne of printed newspapers varies between 890–1060 kg CO_2 equivalents, depending on the landfill assumptions. Using the LF low module for landfill emissions reduces the total carbon footprint by about 16%. The actual amount of GHG emissions from paper disposed to landfill is not known, but currently in Finland the situation is likely somewhere between the two values (see also Chapter 4.1.4).

In the green electricity scenario, the impact of using renewable electricity in the newspaper value chain was studied. Replacing fossil energy sources with renewable ones would diminish the carbon footprint significantly, the result being 485–666 kg CO_2eq/tonne of newspapers. In practice, the availability of different energy sources is dependent on local energy infrastructure, which often cannot be controlled by the actors in the value chain. At the moment, replacing grid electricity with 100% renewable energy is not a realistic option for many industrial actors since Finland does not produce enough renewable energy. However, the scenario provides an indication of the importance of the electricity production mix for the carbon footprint result. Despite the available energy production mix, improving energy efficiency throughout the value chain is very important for reducing the carbon footprint.

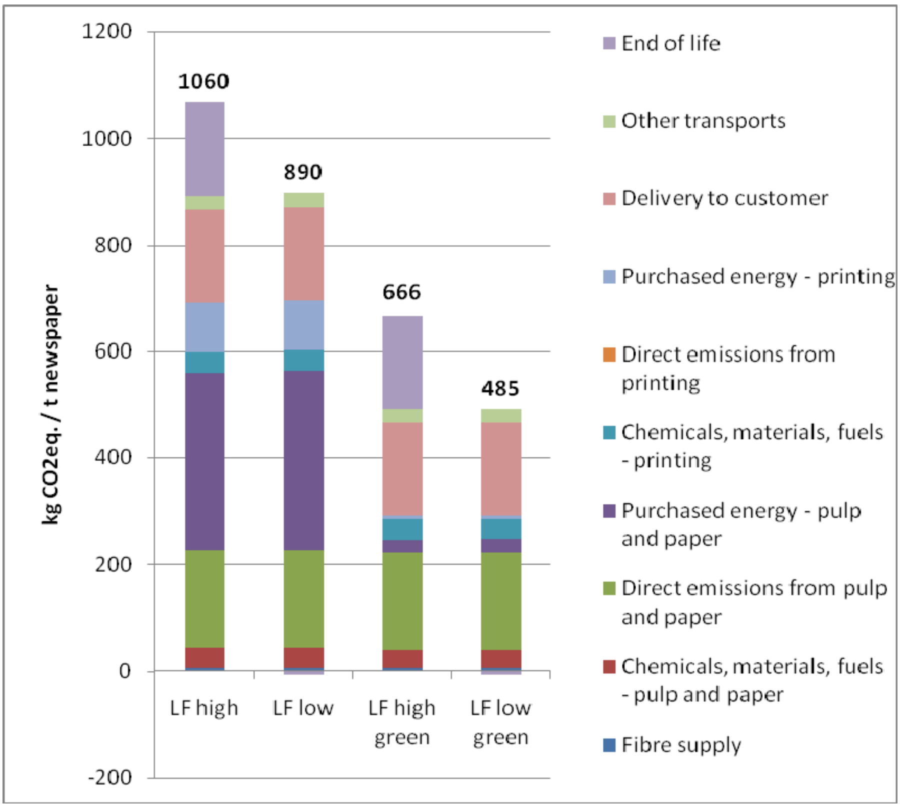


Figure 15. Carbon footprint of a tonne of newspapers in different scenarios.

In addition to one tonne of products, carbon footprints were calculated for one newspaper and for a yearly subscription based on the assumed weight of the product. It was assumed that a newspaper weighs 200 g, includes around 48 pages (broadsheet) and that 356 issues are published each year. As a result, the carbon footprint of one newspaper varies between 180–210 g CO_2eq. When different landfill options are studied – and if a green electricity option is studied – the carbon footprint of one newspaper is about 100–130 g CO_2eq. Results for one newspaper and yearly subscription are presented inTable 11.

Table 11. Carbon footprint of one newspaper and yearly subscription.

	LF high	**LF low**	**LF high, green**	**LF low, green**
Carbon footprint of one tonne of news-papers	1060 kg	890 kg	666 kg	485 kg
Carbon footprint of one newspaper (approx. 48 pages)	0.212 kg	0.178 kg	0.133 kg	0.097 kg
Carbon footprint of yearly subscription	75 kg	63 kg	47 kg	35 kg

5.4.1 Long-distance transportation of recycled fibre

In the basic case, it was assumed that all the recycled paper is collected from Finland. In reality, in order to fulfil the need for recycled paper in newspaper manufacturing in Finland, some recycled paper has to be imported from abroad. The sensitivity of transportation distance for recycled fibre was studied, assuming long-distance transport with a container ship (e.g. from China). In the basic case, the transportation distance was assumed to be the following:

- 75% transported with a 40 t truck, distance 240 km
- 25% by train, distance 300 km.

- In the sensitivity analysis, the assumption was that 100% of the recycled fibre is transported from abroad:

- 100% with a container ship, distance 10 000 km
- land transportation remains the same as in the basic case.

The emissions of the whole system – including the longer transportation distance – are presented in Table 12. The longer transportation distance increases the amount of emitted greenhouse gases and thus the carbon footprint grows by about 10%. Additionally, the amount of both SO_2 and NOx emissions increases notably.

Table 12. Carbon footprint and emissions to air in the basic case, in which recycled fibre is collected from Finland, and in the case in which the transportation distance of recycled fibre increases by 10 000 km.

Emissions from the studied system	Recycled fibre collected from Finland	Recycled fibre transported from abroad
Carbon footprint [kg CO_2eq.]	1060	1164
NOx [kg]	3.4	6.0
SO_2 [kg]	1.0	2.9
TSP [kg]	0.3	0.4

5.4.2 100% end-of-life scenarios

The assumptions made concerning end of life have a significant impact on the carbon footprint of newspapers. In order to find out the range of variation between the emissions from different end-of-life treatments, hypothetical 100% scenarios were carried out, meaning that in each scenario 100% of post-consumer newspaper was assumed to be either recycled, landfilled or incinerated (energy recovery). However, the 100% approach is also highly sensitive to the chosen allocation methodology. In this study, the following allocations were made (see Table 13).

If 100% of post-consumer fibres are incinerated or disposed to landfills, the need for virgin fibre production increases. Both of the systems use recycled fibre as raw material and if the system does not produce any recyclable fibre (as in the case of 100% landfill and 100% energy recovery), additional fibre needs to be produced elsewhere. The environmental burden was allocated by open-loop allocation for recycled paper used as raw material in these systems.

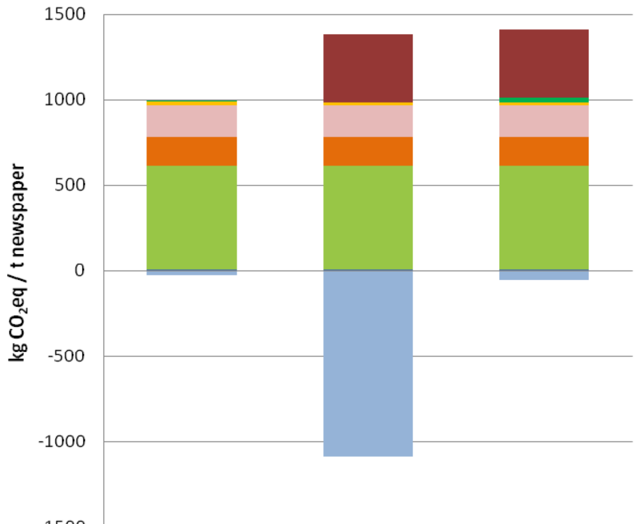
Table 13. Allocations in 100% end-of-life scenarios.

100% to recycling (100% REC)	All the recycled fibre decreases the need for TMP in newspaper production.
100% to energy recovery (100% INC)	Produced energy replaces average Finnish electricity and heat. Environmental load of the recycled paper used in paper manufacturing allocated with open-loop allocation.
100% to landfill (100% LF low)	LF low used as landfill module. Produced energy from landfill gas replaces average Finnish electricity and heat. Environmental load of the recycled fibre used in paper manufacturing allocated with open-loop allocation.

Figure 16 shows the carbon footprint in each 100% end-of-life scenario. The allocation methods and the treatment of produced energy and fibre have a significant impact on the results. It can be seen that when avoided emissions (AE) are taken into account, the carbon footprint is clearly smallest when all of the post-consumer fibres are combusted and the energy is recovered. However, this result is highly dependent on the energy that is being replaced. In areas with a renewable-based energy production structure (e.g. biomass combustion in a co-generation plant), the carbon footprint would be closer to the carbon footprint without avoided emissions (1384 kg CO_2eq/tonne of newspapers).

When 100% of post-consumer fibres are recycled, the carbon footprint is about 970–1000 kg CO_2eq/tonne of newspapers, depending on whether the avoided emissions are taken into account or not. This result is also highly dependent on the allocation methodology for recycled fibre used in the system and leaving the system. In this case, most of the recycled fibre is used within the system (closed-loop allocation, as in the basic case) and the rest decreases the need for TMP production in newspaper manufacturing (system expansion).

If 100% of post-consumer fibres are disposed to landfill, the carbon footprint is larger than in the other cases, amounting to about 1360–1410 kg CO_2eq/tonne of newspapers, depending on whether avoided emissions are taken into account or not. In this case, a landfill with better efficiency and less emissions was used and thus the carbon footprint would be even bigger with other landfill assumptions.



	100% REC	100% INC	100% LF low
Total with avoided emissions	970	300	1360
Total without avoided emissions	1000	1380	1410
Need for additional fibre	0	398	398
End of life	3	0	26
Transports	27	19	19
Delivery to customer	183	183	183
Printing total	167	167	167
Pulp and Paper total	611	611	611
Fibre supply	6	6	6
Avoided emissions	-27	-1086	-52

Figure 16. Carbon footprints in different 100% end-of-life scenarios (100% to recycling, 100% to energy recovery, 100% to landfill) [kg CO_2eq/tonne of newspapers]. Note! Avoided emissions are not subtracted from emissions in the bars and can be seen as negative values in the figure.

Table 14 shows that even though the smallest carbon footprint is seen in the energy recovery (incineration) scenario, nitrogen oxides and particles – and partly also the sulphur dioxides – are at a higher level than when newspapers are recycled. Emissions are presented with and without avoided emissions due to the sensitivity of the assumptions made concerning avoided emissions.

Table 14. NOx, SO_2 and TSP emissions to air during the life cycle of newspaper in different 100% end-of-life scenarios with and without avoided emissions (AE). (100 % to recycling, 100% to energy recovery, 100% to landfill).

Emissions from the studied system	**100% REC**		**100% INC**		**100% LF low**	
	With AE	Without AE	With AE	Without AE	With AE	With out AE
NOx [kg]	3.4	3.6	5	6.8	4.8	4.9
SO_2 [kg]	1.2	1.2	0.3	2.0	1.6	1.7
TSP [kg]	0.34	0.35	0.56	0.74	0.49	0.49

100% scenarios prove that from the carbon footprint point of view, newspapers should not be disposed to landfills. When considering whether to recycle or utilize the energy content of a newspaper, local conditions (such as transport distances) should be taken into account and a more detailed examination should be carried out. However, it should be remembered that if larger amounts of post-consumer fibres are combusted in energy recovery, more primary pulp production is needed to fulfil fibre demand in newspaper manufacturing, which in turn might lead to changes in production and economical structure and to higher greenhouse gas emissions in the long run.

5.5 Life cycle impact assessment results

The life cycle inventory data of four scenarios (excluding the 100% end-of-life scenarios) for the newspaper life cycle were interpreted with the ReCiPe life cycle impact assessment (LCIA) method. This method assesses the potential environmental problems caused by the inventoried emissions and use of resources. In an LCIA, environmental problems are called impact categories. In the newspaper case, seven impact categories were included in the assessment, namely climate change, terrestrial acidification, freshwater eutrophication, photochemical oxidant formation, particulate matter formation, mineral resource depletion and fossil resource depletion. The LCIA methodology and the impact categories are described in Chapter 2.1.4.

The LCIA results were normalized in order to enable the comparison of the results for different impact categories against each other. Normalization has been performed against the environmental impacts caused by one European inhabitant during one year. The normalized results mean that if the climate change impact of the pulp and paper phase (for one tonne of newspapers) were to be equal to the climate change impact of one European during one year, the length of this impact column would be one.[2] More importantly, however, the figures give an overall picture of the potential environmental impacts caused by the newspaper life cycle. Comparisons should be done between the different life cycle phases, pointing out the phases that are significant to the overall environmental performance of newspaper and identifying the development needs.

According to the LCIA results, the life cycle phases of pulp and paper production, printing and transport are responsible for the majority of impacts potentially produced by the life cycle of newspapers (Figure 17 and Figure 18). The fibre supply phase has little impact compared to the other phases. The end-of-life phase may have a significant contribution to climate change impacts, if assuming a high paper degradation rate and low landfill gas collection rate (LF high).

The majority of the impacts in the categories climate change, terrestrial acidification and particulate matter formation are due to energy and fuel use in the system. Climate change impacts are caused by greenhouse gas emissions, mainly CO_2. Acidification is mainly caused by sulphur and nitrogen oxide emissions, which also have a role in particulate formation. Most of the particulates originate, however, directly from the emissions of industrial activities, energy production and traffic. Small particulates can penetrate deep into the lungs and cause respiratory disorders.

[2] In Europe, the average consumption of paper products is approx. 155 kg per person in one year. An average Finnish person consumes approx. 230–240 kg of paper products per year (Finnish Forest Industries Federation 2010). One yearly subscription of newspapers weighs approx. 70 kg and thus one tonne of newspapers equals approx. 14 year-subscription.

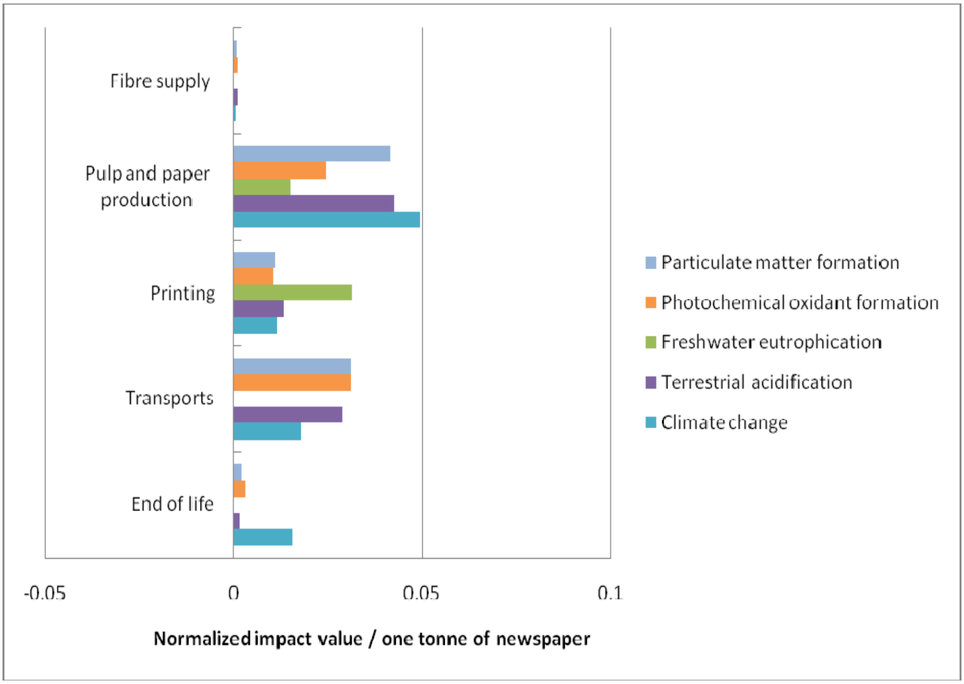


Figure 17. Results of life cycle environmental impact assessment for one tonne of newspapers (Basic case, LF high scenario). Environmental impact of one European inhabitant per year = 1.

Freshwater eutrophication impacts are caused by the phosphorus emissions from pulp and paper production and the printing ink manufacturing chain. Eutrophication leads to changes in species, to algae blooms and to excess shoreline vegetation. The photochemical oxidant formation impacts are mostly due to nitrogen oxide emissions produced by heat and power production and transportation vehicles. Methane, and carbon monoxide also give rise to photochemical oxidant formation. Ozone and other photo-oxidants cause breathing problems, damage to plant leaves and reduced grain harvests.

In view of the potential impacts in the resources depletion categories (both fossil and mineral) (Figure 18), the pulp and paper production phase is clearly the biggest contributor. The depletion impact is assessed by comparing the magnitude of use against the known reserves. The mineral resources depletion impact is almost solely caused by the grid electricity used in pulp and paper production. Uranium is an important fuel in the production of the average Finnish grid mix, where the share of nuclear power is 28% (see Appendix C). Also the fossil resources depletion impacts are connected to energy use in the product system.

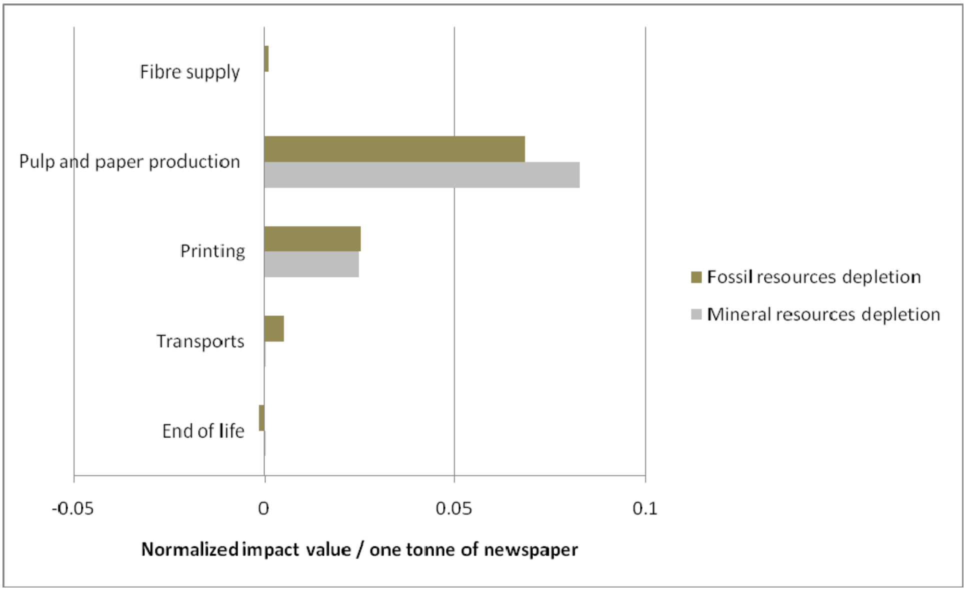


Figure 18. Results of life cycle impact assessment of resource depletion for one tonne of newspapers (Basic case, LF high scenario). Environmental impact of one European inhabitant per year = 1.

The origins of the impacts can be specified by taking a closer look at the life cycle phases pulp and paper production (Figure 19), printing (Figure 20) and transport (Figure 21). The three phases can be separated further in pulp and paper production: direct emissions to air and water, purchased energy (grid electricity and heat) and chemicals, materials and fuels (Figure 19). Fuel and energy use in pulp and paper production produces the majority of environmental impacts, since most impacts are caused by the use of purchased energy (Figure 19). Also direct emissions to air from pulp and paper manufacturing are mainly caused by the power production facility at the site and thus the origin of the impacts is energy use. The third life cycle phase included in pulp and paper production is chemicals, materials and fuels manufacturing and acquisition, in which fuels also have a major role, e.g. for the impacts of resources depletion. The freshwater eutrophication impacts from the direct emission phase are due to phosphorus emissions to water from pulp and paper mills.

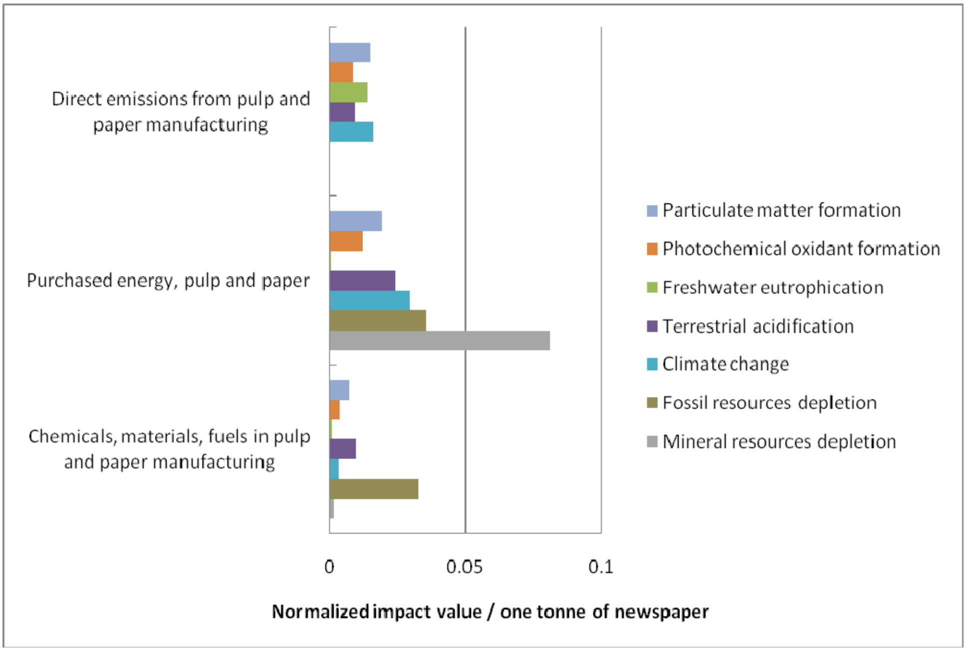


Figure 19. Life cycle impact assessment results for the pulp and paper production phase for one tonne of newspapers (Basic case, LF high scenario). The pulp and paper production phase is divided into three phases. Environmental impact of one European inhabitant per year = 1.

The printing phase can further be divided into the same three life cycle phases as the pulp and paper production phase (Figure 19). Energy and fuel use is the origin of most of the impacts of printing as well. The direct emissions from the printing phase only include emissions of volatile organic compounds to air, which cause photochemical oxidant formation impacts. The freshwater eutrophication impacts of chemicals and materials manufacturing and acquisition originate from phosphorus emissions to water from the manufacturing chain of the partly biobased printing ink used in the product system.

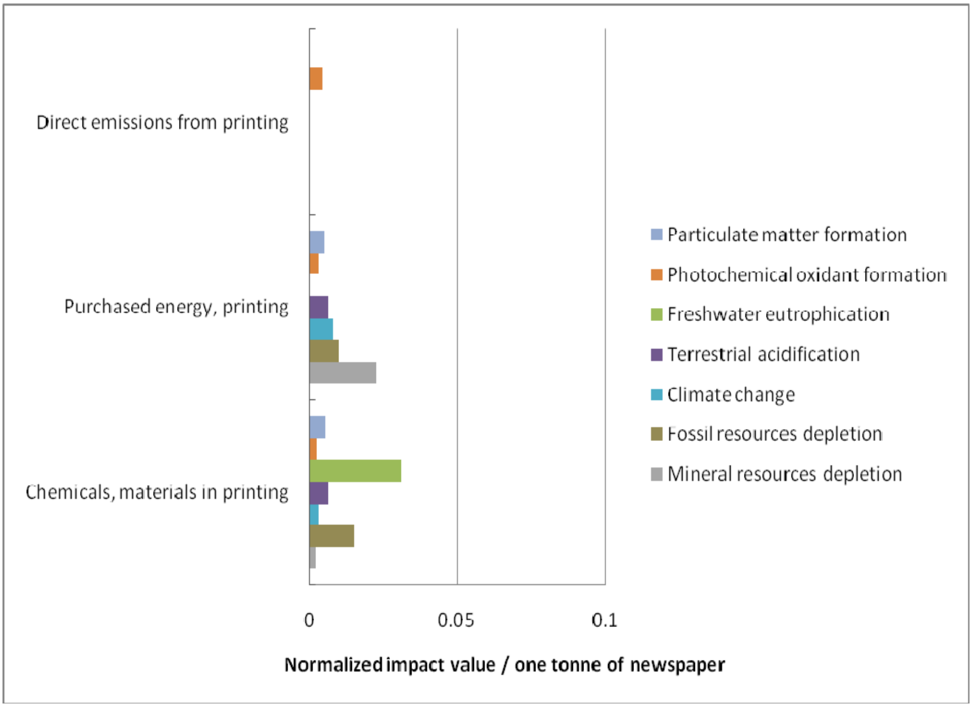


Figure 20. Life cycle impact assessment results for the printing phase for one tonne of newspapers (Basic case, LF high scenario). The printing phase is divided into three phases. Environmental impact of one European inhabitant per year = 1.

The predominant phase for impacts originating from transport in the system is the delivery of newspapers to consumers. This phase is managed with small vehicles delivering small amounts of papers. In Figure 21 no fossil resources depletion impacts originate from the delivery phase, which is due to the lack of data on the fuel consumption of the vehicles.

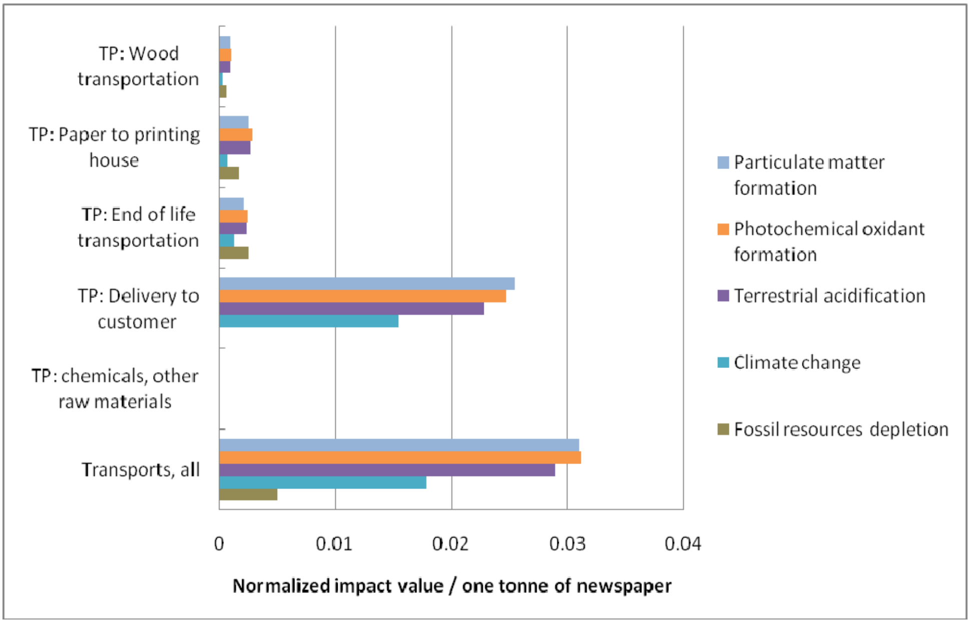


Figure 21. Life cycle impact assessment results for one tonne of newspapers (Basic case, LF high scenario). The transport phase is further divided into five phases. Environmental impact of one European inhabitant per year = 1.

In addition to the basic case (with higher emissions from the landfill, LF high), an LCIA was performed for three other scenarios:

– basic case with lower emissions from the landfill (LF low)
– green grid electricity with higher emissions from the landfill (LF high, green)
– green grid electricity with lower emissions from the landfill (LF low, green).

The scenarios are compared in Figure 22. The difference between the LF high and LF low scenarios is that the climate change impact is lower in the latter because waste paper landfilling results in less methane emissions (Figure 22). This causes a 17% reduction in climate change impacts compared to the overall climate change impacts of the LF high scenario. The use of green grid electricity in the scenarios 'LF high green electricity' and 'LF low green electricity' decreases the impacts in all the impact categories except for freshwater eutrophication. The decrease can most clearly be seen in the climate change impacts and both fossil and mineral resources depletion impacts where the reductions are 38%, 47% and 97% respectively when compared to the LF high scenario.

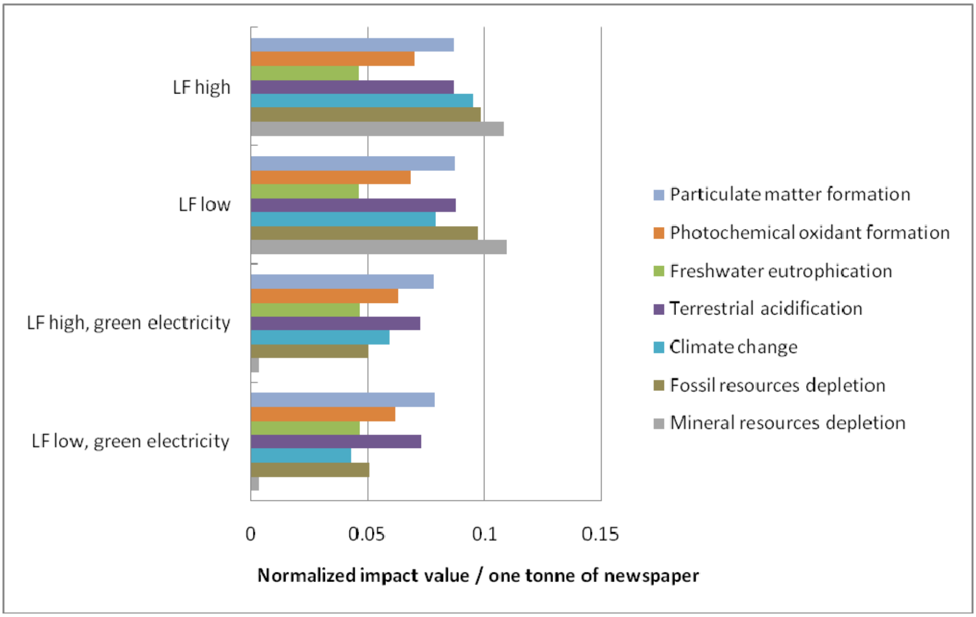


Figure 22. Comparison of life cycle impact assessment results for the different newspaper scenarios: LF high (Basic case), LF low (Basic case), LF high green electricity and LF low green electricity. Environmental impact of one European inhabitant per year = 1.

5.6 Conclusions and discussion

The potential environmental impacts of a typical Finnish regional newspaper were evaluated using LCA methodology, carrying out an inventory analysis and environmental impact assessment. The results indicated that paper manufacturing (incl. fibre supply, direct emissions from pulp and paper mills, raw material manufacturing and purchased electricity) was the biggest contributor to SO_2 and TSP emissions. The printing phase (including chemicals, materials and fuels needed in printing and purchased electricity) contributes about 8% of total NOx emissions, about 25% of SO_2 emissions and about 15% of total TSP emissions. Home delivery of newspapers creates most of the NOx emissions (41%) and 21% of the TSP emissions. Most of the VOC emissions come from printing houses (~64%) and from printing ink manufacturing (~14%).

Pulp and paper mills are the biggest contributor of studied COD (95%), TSP (94%), Ntot (50%) and Ptot (84%) to water. In addition, manufacturing of chemicals, materials and fuels for printing has a significant contribution to water emissions: 46% of Ntot, 15% of Ptot and 5% of COD emissions. Most of these emissions originate from manufacturing of vegetable oil-based printing ink. It stands to reason that paper manufacturing accounts for a large share of many emission categories since paper is the main raw material and substrate of the product and forms most of the weight of the final product.

Based on the life cycle inventory results, the carbon footprint for one tonne of printed newspaper varies between 890–1060 kg CO_2 equivalents with different landfill modules. If renewable electricity would be used in the value chain, the carbon footprint would be diminished significantly to 485–666 kg CO_2eq. This result underlines the significance of the energy production mix for the carbon footprint results.

A typical daily print run of a regional newspaper in Finland is assumed to be 80 000 copies at most. 80 000 copies of a newspaper weighing 200 g equal 16 tonnes of print products in this case study. The carbon footprint for this amount of newspapers (including the whole life cycle of products) is approximately 16–17 t CO_2eq, depending on the landfill assumptions. This is equivalent to the yearly GHG emissions from the electricity use of 3–4 typical Finnish houses with electrical heating or 22–26 Finnish flats with district heating[3].

On the other hand, the GHG emission per one 200 g newspaper (approx. 48 pages, broadsheet) is about 180–210 g CO_2eq. This equals the GHG emissions caused by driving a car for about 1.1–1.3 km[4] or the electricity consumed by watching a modern TV for about 5–6 hours in Finland[5]. It should be noted that this figure only includes the electricity consumption of watching TV, and manufacturing, electronic transmission and disposal and recycling are excluded.

The potential contribution of the newspaper product system to environmental impacts is mostly connected to the energy and fuels used in different life cycle phases. The introduction of green grid electricity decreases impacts in all impact categories except for freshwater eutrophication. However, biomass use for en-

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[3] An average 120 m^2 Finnish house for four persons (with electrical heating) consumes 18 MWh of electricity per year. An average 75 m^2 Finnish flat for three persons in an apartment building (with district heating) consumes 2.6 MWh of electricity per year. (Adato Energia 2008, Fortum 2010). The emission factor for Finnish electricity from grid is 250 kg CO_2eq/MWh.

[4] A new passenger car emits on average 164 g CO_2eq./km (lipasto.vtt.fi).

[5] A modern 32-37'' LCD TV set consumes 0.15 kWh_e/h (Helsingin Energia 2010). This is the predominant technology in Finnish homes now and in the near future (Adato Energia 2008). The emission factor for Finnish electricity from grid is 250 kg CO_2eq/MWh.

ergy may have unwanted impacts on, for example, food supplies, land use and the role of forests and soil as carbon sinks. These impacts are currently still difficult to assess in the LCA methodology.

The pulp and paper industry has made great efforts to reduce nutrient emissions from pulp and paper production. Such emissions have significantly decreased, but they still have the potential to contribute to the eutrophication of freshwaters. Thus nutrient emissions should not be neglected. Greater attention should be given, however, to the printing ink manufacturing chain, which has a high contribution to the potential freshwater eutrophication impacts. The ink modelled here may not be exactly the one used by Finnish printing houses. (The ink used in the LCA was a combination of different offset inks. In reality, there are great differences between inks used for different offset methods. See also Chapter 3.) Nevertheless the results indicate that although a change towards the use of biobased instead of mineral-based materials is commonly considered a positive change, it can cause unexpected adverse impacts in the overall system. This also emphasizes the need for comprehensive environmental impact assessments when planning changes in manufacturing and production systems.

It must be kept in mind, however, that the impacts assessed in the LCIA do not cover all environmental impacts potentially caused by the newspaper life cycle. There are two main reasons for this, namely 1) data gaps, e.g. concerning the emissions of metals and hazardous organic compounds to air which cause human toxicity and ecotoxicity impacts, and 2) methodological deficiencies, e.g. in assessing the land use impacts in terms of loss of biodiversity and recreational values and degradation of landscapes and in assessing the impacts of odour and noise.

6. Life cycle assessment and carbon footprint of a heatset offset printed magazine

Chapter 6 presents the results of an LCA and carbon footprint case study for a heatset offset printed magazine. The case product is a weekly magazine and it is assumed that the magazine is manufactured and read in Finland.

The product category ‘magazines’ includes several kinds of publications that are published at least four times a year, e.g. organizational and trade journals, customer magazines, hobby magazines and women’s magazines. In 2008, over 3000 different magazines were published in Finland, and 55 of them were weeklies. The circulation of journals and periodicals was around 13.7 million in 2008. The share of customer magazines was one third (1/3) of the total circulation amount (VKL & GT 2009). Finns commonly subscribe to magazines. In 2008, 95% of magazines were delivered to homes (over 370 million copies) while the rest (5%, about 21 million copies) were sold by retailers (Aikakausmedia 2009). The amount of time Finnish readers dedicated to the reading of magazines in 2007 was around 19 minutes per day (Statistics Finland 2008). On average a Finnish person reads (follows) 6–7 magazines (KMT 2009).

Magazines can be published both in print and electronically. In general, magazines are printed in varying sizes using different methods on several kinds of papers. In Finland, heatset offset printing is commonly used for the economical production of magazines. It is a process that employs fast presses with web widths from 0.5 to 2.5 metres. There are many heatset printing houses and each house normally has several printing presses. Typical print runs are between 8 000 and 250 000 copies.

Offset lithography is a complex printing process in which the printing plate is divided into chemically differing image and non-image areas, where the difference is induced by photochemical reaction. In the printing process, the plate is first dampened with a fountain solution, which adheres to the non-image areas of the plate. In the following stage, nip ink rollers apply ink only to the image areas of the printing plate. The image on the plate is transferred via a rubber blanket to the substrate under nip pressure. The print quality of heatset printing is high and is heavily influenced by the quality of the substrate.

Inks used in heatset offset are mineral or vegetable oil-based and they dry by evaporation of the ink solvents. The ink solvents and the alcohol used in the fountain solution are cleaned from the outflow of the dryer with an afterburner. The aluminium-based printing plates are recycled.

Magazine covers are printed on coated fine paper, which is a high-quality printing paper made from bleached chemical pulp. The term woodfree paper is also used. In chemical pulping, wood chips and chemicals are combined in digesters where heat and chemicals break down the lignin to separate the cellulose fibres from each other without seriously degrading them. The kraft process is the dominant chemical pulping method. Coating the paper gives it a smooth and even surface and enables very high print quality. The clay and calcium carbonate ($CaCO_3$) coating is usually made with two layers and the top coating is done as blade coating.

The inner sheets of the magazine are lightweight coated paper (LWC), which is made mainly from mechanical pulp. Long-fibre chemical pulp is added to gain strength. Thermomechanical pulp (TMP) is made from wood chips that are treated in a TMP refiner with the help of pressure and heat to separate the fibres. TMP also contains the lignin from the wood. LWC paper typically has a pigment coating layer of clay and calcium carbonate ($CaCO_3$) of 5 to 12 g/m^2/side for better surface strength and print quality. Binders are used in LWC paper in the base paper (starch) and also in the coating layer (starch, SB latex or polyvinyl alcohol (PVA)) to give the paper the wet strength and surface strength it needs.

6.1 Case definition

The goal of the case study was to examine the potential environmental impacts of a typical Finnish weekly magazine. The basic parameters and assumptions related to the case product were defined together with paper and printing industry representatives. The case study does not present data related to any particular Finnish magazine. Rather, it describes a hypothetical case, thereby providing an example of the potential environmental impacts in this product group.

The functional unit used in the study was 1000 kg of magazines. Carbon footprints were calculated for both one magazine and a yearly subscription based on the assumed weight of the product. The scope of the study was cradle to grave, which means that it covered the whole life cycle of a magazine, from raw material manufacturing until the disposal of the read magazine. Magazine editorial work was not included in the study. Table 15 presents the case study assumptions and a detailed case definition.

Table 15. Case study assumptions for an HSWO printed magazine.

Print product	Weekly magazine, 56 and 86 pages, 22 x 30 cm
Printing	Heatset web offset (HSWO), 4-colour printed
Paper	Cover: 150 gsm coated fine paper Inner sheets: 80 gsm LWC paper
Circulation	70 000–80 000
Yearly subscription	48 issues
Weight and dryness	170 g and 250 g/issue, dryness 96%
Geographical aspects	Paper production, printing, delivery and disposal in Finland
Distribution	Delivery to home
End-use of product	Recycling 83% Landfill 16% Incineration 1%

A cradle-to-grave approach was applied, meaning that the life cycle was studied from raw material extraction until the end-of-life treatment. The paper mills were assumed to be integrated with pulp mills. The LWC paper furnish was assumed to be 42% spruce TMP, 20% pine kraft, 35% pigments and 3% binders. The furnish for the coated fine paper that was utilized for magazine covers was 18% pine kraft, 42% birch kraft, 35% pigments and 5% binders. The auxiliary fuels used for heat production at the paper mills are mainly natural gas and peat. Data on paper manufacturing was derived from the KCL Ecodata database. For production of grid electricity and heat, a five-year Finnish average was used. The electricity and heat production mixes are presented in Appendix C.

Data on printing was collected from Finnish magazine printers. The assumed maculature percentage in the printing house was 27%. Data on printing ink was derived from the Ecoinvent database, representing average data on offset printing ink. The offset printing ink used in the study includes both mineral and vegetable oils. Data on printing plates is based on the Life Cycle Inventory data of the European Aluminium Association (EAA 2008). Data sources and data age are presented in detail in Appendix F. The distribution of the print product is assumed to happen as home delivery, and thus retail sale is excluded from the study. Figure 23 shows the system boundary of the studied system with fibre flows (moist).

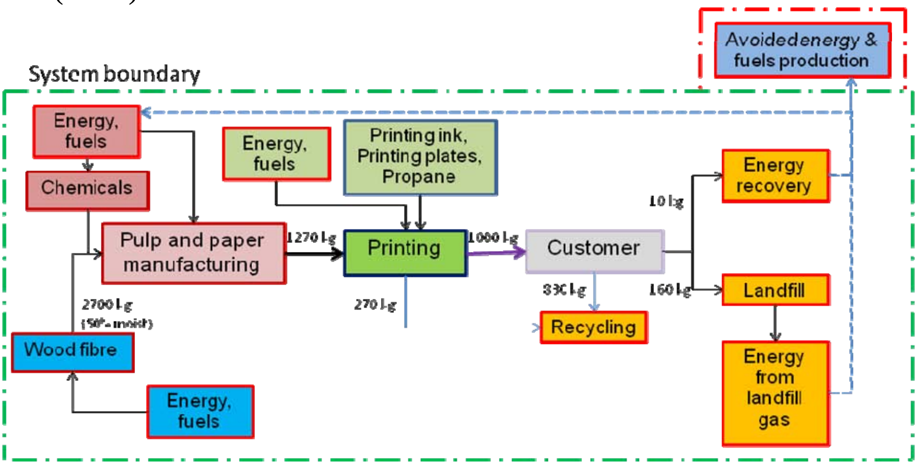


Figure 23. System boundary of the studied magazine with wood fibre flow (moist).

To study the significance of the made assumptions, several additional scenarios and sensitivity analyses were included in the study. Two different landfill options were studied to examine the impact of methane emissions caused by paper disposed to landfill (for more information, see Chapter 4.1.4). The impact of replacing purchased electricity at printing houses with renewable electricity was studied in a green electricity scenario. The production mix of renewable electricity was based on Finnish energy statistics (IEA 2008). The used production mix for green electricity is: ~58% hydropower, ~41% biomass and ~1% windpower. Additionally, the impact of different allocation methods for the large amount of recycled fibre produced by the system was studied. The allocation methods are described in Chapter 6.2.2.

A life cycle inventory and carbon footprint calculation were conducted for all scenarios. In addition, the carbon footprint of the plastic wrapping of magazines was calculated. The studied scenarios are presented in Table 16.

Table 16. Studied scenarios in the magazine case. Basic case highlighted with orange.

Case	**Landfill option**	**Electricity**	**End-of-life treatment**
LF high, basic case • No allocation • Open-loop allocation • Avoided emissions	High	5-year average Finnish grid electricity	83% recycling 16% landfill 1% incineration
LF low	Low		
LF high, green electricity purchased in printing house	High	Green electricity to printing house	
LF low, green electricity purchased in printing house	Low	Green electricity to printing house	

A life cycle impact assessment (LCIA) was conducted for the following scenarios:

- landfill with higher emissions (LF high, basic case)
- landfill with lower emissions (LF low)
- landfill with higher emissions and open-loop allocation (LF high, alloc)
- landfill with higher emissions, and avoided emissions (LF high, AE).

Some of the earlier results of this case study have been presented in the 36th International Research Concference of iarigai in Stockholm, September 2009 and published in the proceedings (Pajula et al. 2009). Since then, the results have been updated and modified.

6.2 Allocation procedures

When the life cycle of the magazine was modelled, different allocation methods were applied. Allocation was conducted for the recycling of printing plates used in printing houses and for recycled fibre produced in the system. In addition, system expansion was conducted for excess energy produced in the product system. All the allocations are explained in the following subchapters. (For more information about allocations, see Chapter 4.1.5.)

6.2.1 Allocation of printing plates

Printing plates in magazine manufacturing are manufactured from primary aluminium. Data on aluminium is based on the LCA study of the European Aluminum Association (EAA 2008) and the data received from the EAA. Printing plates are manufactured 100% from primary aluminium and the recycling of the plates is very efficient. In this study, it was assumed that 97% of printing plates are recycled and the loss in the recycling process is about 0.7%. Open-loop allocations were used because the further use of recycled printing plates was not known. The principles of open-loop allocations are presented in Appendix G.

Open-loop allocation gave an allocation factor of 13.6% for the primary aluminium, and the rest (86.4%) of the inputs and outputs are allocated to the recycled printing plates. The allocation percentage for recycled aluminium is rather high due to the high recycling rates and good recyclability of aluminium.

6.2.2 Allocation of recycled fibre

In the study, it was assumed that 83% of magazines are recycled. Magazines are produced from primary fibre and none of the recycled material produced in the system can be reutilized in the system. In addition to post-consumer recycling, maculature from printing houses can be recycled and used as a raw material in paper manufacturing. Altogether, the studied system produces 1100 kg of recycled fibre (maculature from the printing house and recycled magazines from consumers).

Recycled fibre can be considered to be a by-product of the system which can be used as a raw material in another product system. Thus it is justified to allocate some of the environmental burdens to recycled fibre. ISO 14040-44 standards recommend the use of system expansion to avoid actual allocation, but because several methods are possible in the magazine case and it is difficult to say that one is better than the other, the sensitivity of chosen allocation methods is studied.

The following allocation methods were applied in this case study:

- **Cut-off allocation**, meaning that the system does not benefit from the recycled fibre that it produces. Cut-off allocation was used in the basic case (Figure 23).

- **Open-loop allocation**, meaning that a part of the emission load is allocated to the recycled fibre leaving the system, thereby providing benefits for the studied product system by producing raw material for another product system. The principles of open-loop allocation are presented in Appendix G. Figure 24 presents the system boundary with open-loop allocation. In this study, 63% of the inputs and outputs from paper manufacturing are allocated to the recycled fibre that is produced in the system. It should be noted that only the inputs and outputs of paper production are allocated, and printing and end of life are allocated in full to the studied magazine.

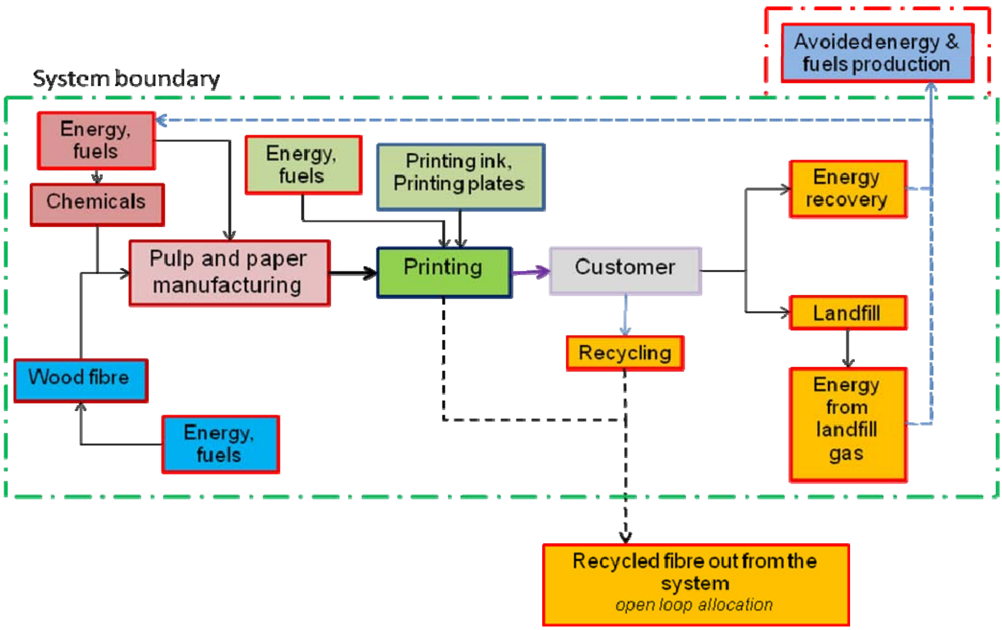


Figure 24. Recycled fibre from the magazine product system allocated out of the system by open-loop allocation.

– **System expansion with avoided emissions** is another way to calculate the benefits from producing raw materials to another product system. In Finland, it is typical for most of the recycled fibre (from magazine and newsprint recycling) to be used in newsprint manufacturing. In this study, recycled fibre was assumed to be used in newsprint manufacturing, thereby avoiding the production of thermomechanical pulp (TMP). Figure 25 presents the system boundary with avoided emissions (system expansion). By means of system expansion, electricity-intensive TMP production can be avoided. On the other hand, the TMP process would produce heat as a by-product and this heat production is also avoided and needs to be replaced by additional heat production. In this study, it is assumed that heat produced in the TMP process replaces average Finnish heat production and when the TMP process is replaced by deinking, more average Finnish heat needs to be produced.

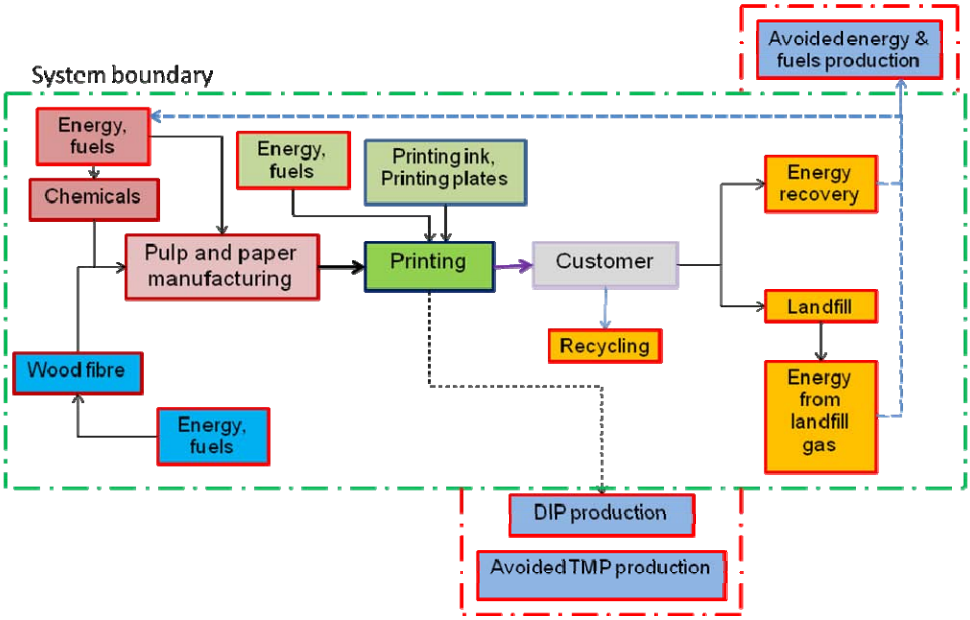


Figure 25. Recycled fibre from the magazine product system avoids thermomechanical pulp (TMP) production in newspaper manufacturing.

6.2.3 Energy produced in the system

After reading, the magazine is either recycled, disposed to landfill or disposed to energy waste. As in the newspaper case, when magazines decay at landfills, landfill gas is produced and part of the gas is collected and burned in either flares or microturbines. The landfill modules LF high and LF low were used in the magazine case (see Chapter 4.1.4). A small proportion of magazines end up in a waste incineration plant that produces heat and electricity. All of the produced electricity is utilized in the studied system. When it comes to heat, the system uses less auxiliary heat than it produces and therefore it was assumed that the produced heat replaces Finnish heat production (system expansion).

6.3 Life cycle inventory results

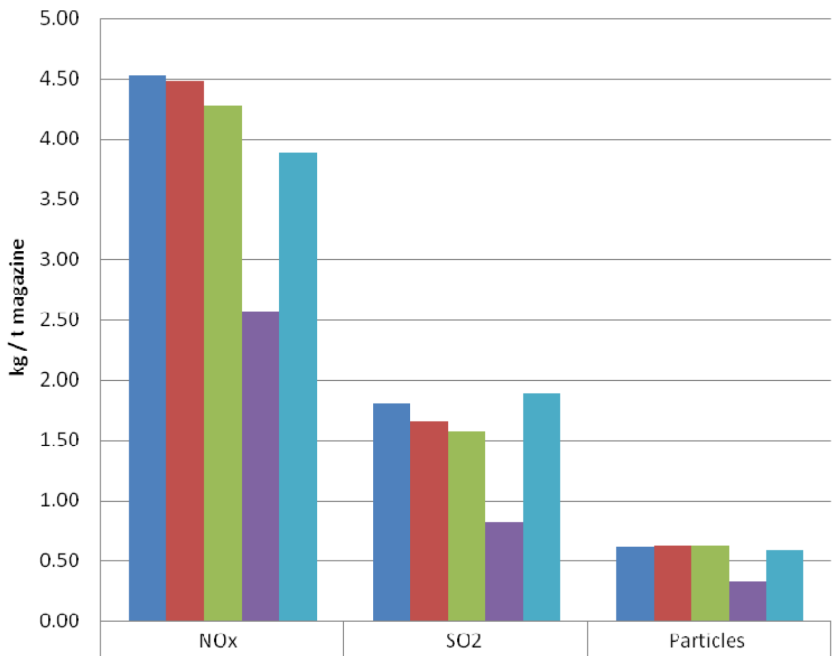
The life cycle inventory (LCI) results presented in this chapter include emissions to air (NOx, SO_2, TSP and VOC) and emissions to water (COD, Ntot, Ptot, TSS). All greenhouse gas emissions are included in the carbon footprint and are reported separately in Chapter 6.5. The aspects related to solid waste are discussed but not reported in detail due to high uncertainty concerning the used background data on solid waste amounts. All LCI results for different scenarios are presented in detail in Appendix E.

6.4 Emissions to air

Figure 26 presents the following emissions to air: nitrogen oxides (NOx), sulphur dioxide (SO_2) and total particulate matter (TSP). (For GHG emissions, see Chapter 6.5.) In addition to the basic case, different magazine scenarios were calculated (for scenario definitions, see Table 16). Two different landfill modules were applied and the impact of switching to renewable grid electricity in the printing house was evaluated. In the green electricity scenario, the grid electricity for the printing house was produced by biomass, hydro and wind power (see Chapter 5.1). Additionally, the impact of different allocation methods for recycled fibre was studied. LCI results from different scenarios are presented in Figure 26.

The LCI results presented in Figure 26 indicate that if part of the environmental load of paper manufacturing is allocated to the recycled fibre leaving the system (LF high alloc.), the emissions are clearly smaller than with other allocation methods (cut off used in the basic case and avoided emissions). Allocating part of the environmental burden to recyclable fibre that can be used as an input for another product system thus reduces the impact that is caused by the production of the virgin raw material. This is a methodological choice that can be used to show the potential environmental benefits of producing recyclable products.

If system expansion is done (LF high, avoided emissions), emissions do not diminish significantly and in fact SO_2 emissions increase compared to the basic case. This is because if TMP is replaced by deinked pulp, heat that is produced as a by-product in the TMP process is also replaced and more auxiliary fuels are needed for heat production at the mill.



	NOx	SO2	Particles
LF high	4.53	1.81	0.62
LF low	4.48	1.66	0.62
LF high, green	4.27	1.57	0.62
LF high, alloc	2.57	0.81	0.32
LF high, AE	3.89	1.89	0.59

Figure 26. NOx, SO_2 and TSP emissions to air in different scenarios [kg/tonne of magazines (air dry tonne)].

Because cut-off allocation was used in the basic case, the results of the scenario also include the emissions caused by the production of recyclable fibre that can be considered to be a side product from the studied system. In the system expansion scenario, the results are sensitive to the assumed use of the recycled fibre. In this case, it was assumed that recycled fibre produced by the studied system replaces production of TMP in newsprint manufacturing. Other possible uses for recycled fibre in Finland could be for example package manufacturing. The results of the scenario with open-loop allocation include the benefit from manufacturing a recyclable product but it is not known in which product the fibre will be used next. As a consequence, results from the scenario with open-loop allocation (LF high, allocation) were considered to be the most relevant ones and were studied more closely.

The NOx, SO_2 and TSP emissions in the LF high scenario are presented in Figure 27. In the scenario, the NO_x emissions originate mainly from delivery to customer (28%), other transport (14%), direct emissions from pulp and paper manufacturing (14%) and purchased energy for pulp and paper manufacturing (13%). The main contributors for life cycle SO_2 emissions are purchased energy production for pulp and paper manufacturing and for printing, 31% and 19% respectively, and chemicals, materials and fuels production for pulp and paper manufacturing and for printing, 16% and 23% respectively. Particulate (TSP) emissions originate more evenly from multiple life cycle stages.

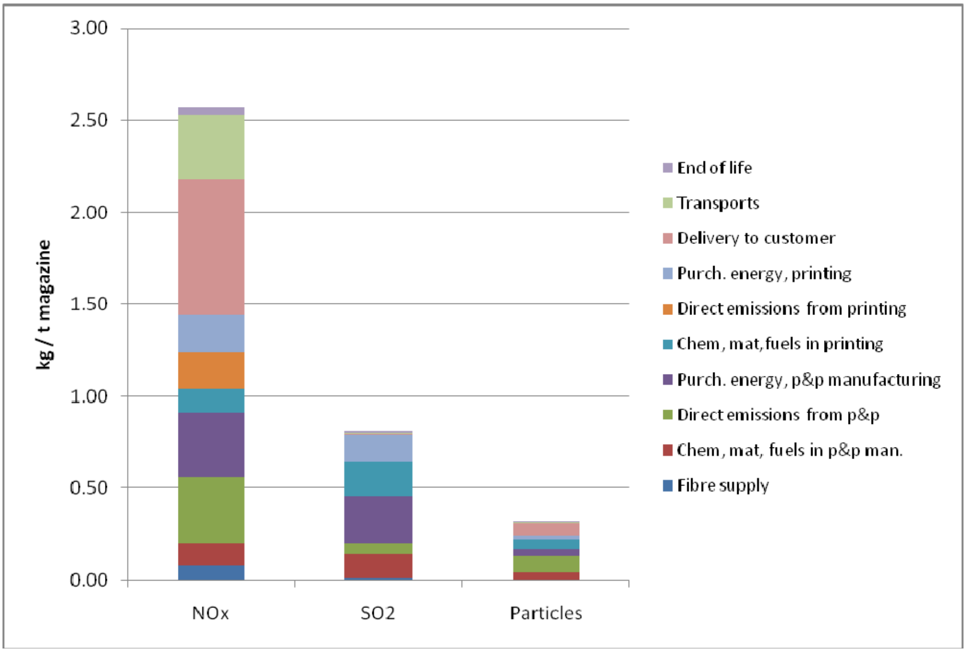


Figure 27. NOx, SO_2 and TSP emissions to air in LF high, open-loop allocation scenario [kg/tonne of magazines (air dry tonne)].

Figure 28 presents the VOC emissions in the LF high, open-loop allocation scenario. Most of the VOC emissions come from printing houses (~70%). In addition, VOC emissions are emitted when chemicals (printing ink and isopropanol) and fuels (propane and natural gas) are manufactured for printing and pulp and papermaking purposes. The assumed consumption of isopropanol was 3 kg / 1000 kg magazines. Some VOC emissions come from sawmills producing chips for pulp and paper mills.

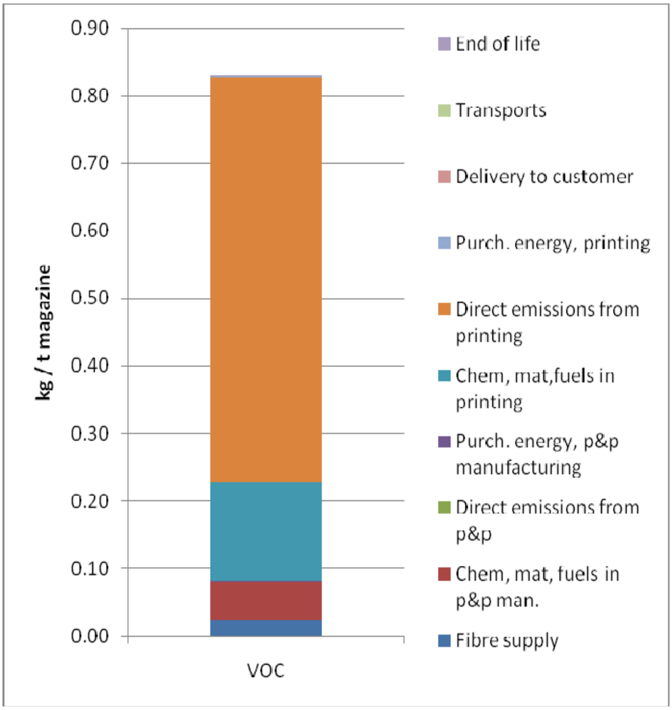


Figure 28. VOC emissions during the life cycle of a magazine in the LF high, open-loop allocation scenario [kg/tonne of magazines (air dry tonne)].

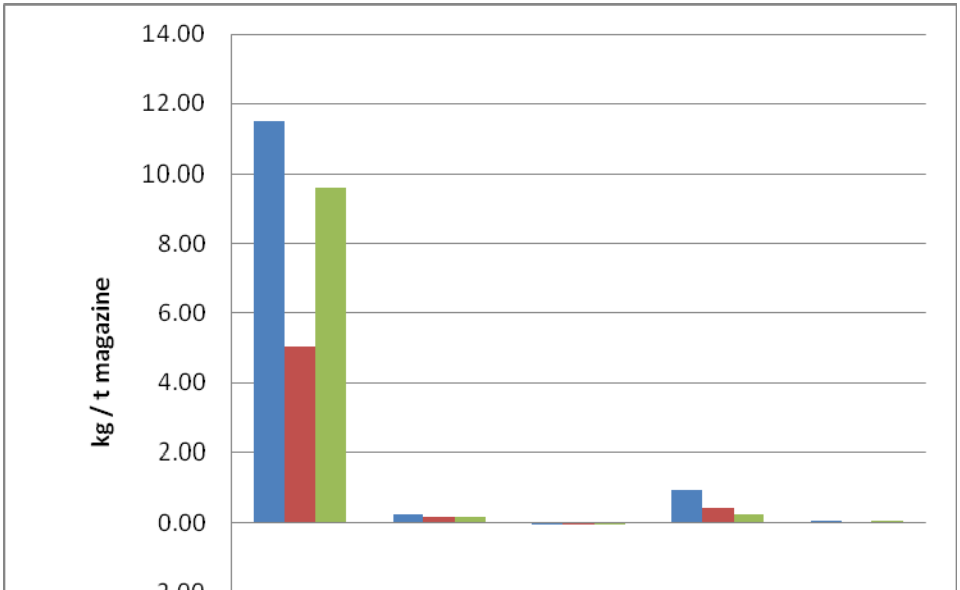
Some variation in VOC emissions can also be seen between the allocations – if recycled fibre is credited from the system either with open-loop allocation or with avoided emissions, VOC emissions allocated to the studied magazine decrease by 5–15%. It should be noted that VOC emissions from the printing house remain the same in all of the cases since allocation does not decrease emissions in the printing phase.

6.4.1 Emissions to water

Chemical oxygen demand (COD), total nitrogen (Ntot), total phosphorus (Ptot), total suspended solids (TSS) and adsorbable organic halogen compounds (AOX) were included in the inventory. The COD figure expresses the amount of organic oxygen-consuming compounds in the wastewater. AOX expresses the amount of chlorine contained in the organic compounds. When released to the water system, nitrogen and phosphorous emissions cause eutrophication. TSS means the amount of solid matter included in the wastewaters.

When comparing the studied scenarios, only the choice of allocation makes a difference between the levels of water emissions between the scenarios. This is because both landfills and the production of purchased electricity have a negligible contribution to studied emissions to water. A significant reduction in water emissions occurs when some of the environmental burden caused by the production of primary fibre is allocated to the recyclable fibre leaving the system (open-loop allocation).

Likewise, the level of water emissions decreases compared to the basic case when the recyclable fibre leaving the system is assumed to produce raw material for newsprint manufacturing, thereby avoiding the production of TMP (system expansion in the avoided emissions scenario). Figure 29 presents the studied emissions to water in the basic case (LF high) with cut-off allocation, with open-loop allocation and with avoided emissions.



	COD	Ntot	Ptot	TSS	AOX
LF high	11.51	0.25	0.01	0.93	0.057
LF high, alloc	5.05	0.17	0.01	0.39	0.021
LF high, AE	9.59	0.17	-0.01	0.26	0.057

Figure 29. Emissions to water during the life cycle of a magazine with different allocation methods [kg / tonne of magazines].

Table 17. Emissions to water during the life cycle of a magazine in the LF high, allocation scenario (kg/tonne of magazines).

Emissions to water	**COD**	**Ntot**	**Ptot**	**TSS**
Chemicals, materials, fuels in pulp and paper manufacturing	0.02	0	0	0.01
Direct emissions from pulp and paper manufacturing	3.74	0.047	0.001	0.3
Chemicals, materials, fuels in printing	1.28	0.121	0.005	0.08
Total	**5**	**0.17**	**0.006**	**0.39**

Table 17 presents the sources of emissions to water in the LF high, allocation scenario. Pulp and paper mills and chemicals, materials and fuels production for printing are the two biggest contributors to the COD, Ntot and TSS emissions. In the scenario 74% of COD, 28% of nitrogen, 15% of phosphorous and 76% of TSS emissions originate from pulp and paper manufacturing. TSS emissions (total suspended solids) from pulp and paper mills can include, for example, small fibre fragments and filler and coating substances. Nitrogen and phosphorous emissions originate from the wastewater purification process at the mills.

Another major contributor is the manufacturing of printing ink, which produces the largest share (83%) of the phosphorous emissions and nitrogen emissions (72%) in addition to 25% of COD and 21% of TSS emissions. AOX emissions originate mainly from pulp and paper manufacturing.

6.4.2 Solid waste

In addition to emissions to air and water, the manufacturing of magazines produces solid waste. When cradle-to-grave solid waste amounts are calculated (but consumer waste is excluded), the amount of solid wastes allocated for manufacturing one tonne of magazines is about 340 kg. The total amount includes 270 kg (80% of the total waste amount) of maculature from the printing house. The maculature ends up in paper recycling. Most of the solid waste created during the life cycle of a magazine is either recyclable or combustable. Landfill waste can include, for example, ash from pulp and paper manufacturing and some mixed waste from the printing house.

Additionally, a small amount of hazardous waste is produced. The amount of hazardous waste equals 0.5% of the total waste amount. However, the amounts of solid waste contain considerable uncertainty because the completeness of data related to solid waste along the magazine value chain is poor and therefore the amounts of solid waste are not reported in more detail.

6.5 Carbon footprint results

The carbon footprint includes the greenhouse gas emissions produced during the entire life cycle of products (see also Chapter 2.2). Different scenarios were examined in the magazine case. As mentioned previously and as shown inTable 16, two landfill options and the impact of purchasing green electricity for the printing house were studied. In addition, the impact of the choice of allocation methods affects the carbon footprints significantly. The following figure (Figure 30) shows the variation in carbon footprints depending on the scenario assumptions.

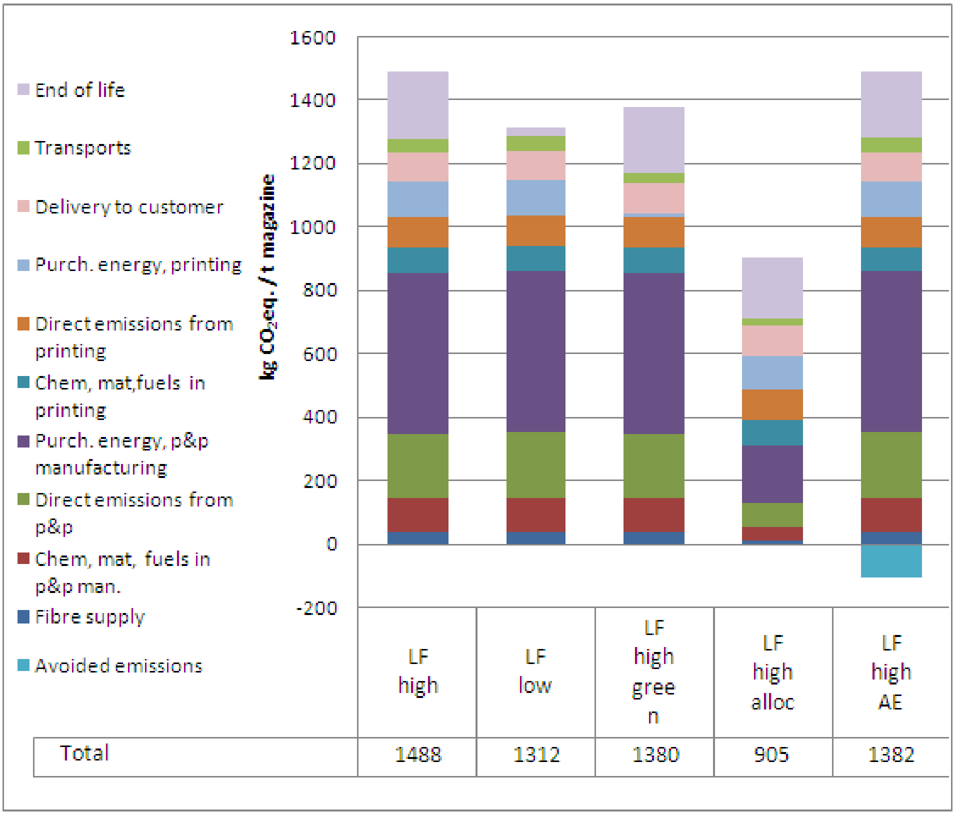


Figure 30. Carbon footprint for one tonne of magazines (air dry tonne) in different scenarios. Bars from left to right: 1) basic case with higher landfill emissions, 2) basic case with lower landfill emissions, 3) higher landfill emissions and green grid electricity in printing, 4) higher landfill emissions and open-loop allocation of recyclable fibre, 5) higher landfill emissions and avoided emissions due to production of recyclable fibre.

If a landfill with higher gas collection efficiency and lower landfill gas emissions is considered, the carbon footprint of one tonne of magazines would be 1351 kg CO_2eq, about 11% smaller than in a landfill with higher emissions. The difference between the higher and lower level of GHG emissions from paper disposed to landfill is 176 kg CO_2eq. The actual amount of methane emissions created at the landfill site involves a degree of uncertainty, but it is assumed that the situation in Finland is somewhere between these two figures (see also Chapter 4.1.4). Switching from average Finnish grid electricity to green grid electricity in a printing house would decrease the total carbon footprint by 7% (to 1418 kg CO_2eq) compared to the basic case.

Different allocation methods for recycled fibre lead to different carbon footprints. Open-loop allocation reduces the carbon footprint remarkably (by 40%). In the case of open-loop allocation, it is considered that 40% of the carbon footprint is transferred to the other product system using the recycled fibre as an input for new products. Thus the actual amount of created emissions does not decrease; rather, the smaller carbon footprint shows the potential benefits of the good recyclability of the product.

System expansion does not decrease the amounts of greenhouse gas emissions all that much (7%). In the system expansion, the amount of avoided emissions is small due to the fact that when TMP manufacturing is avoided, the heat that is produced as a by-product in TMP manufacturing needs to be produced with auxiliary fuels. In this study, it is assumed that the required heat is fulfilled with Finnish average heat production and thus greenhouse gas emissions increase – and, in fact, avoided emissions decrease.

The cradle-to-grave carbon footprint for one tonne of magazines in the LF high open-loop allocation scenario is 905 kg CO_2eq. The result is presented in Figure 32.

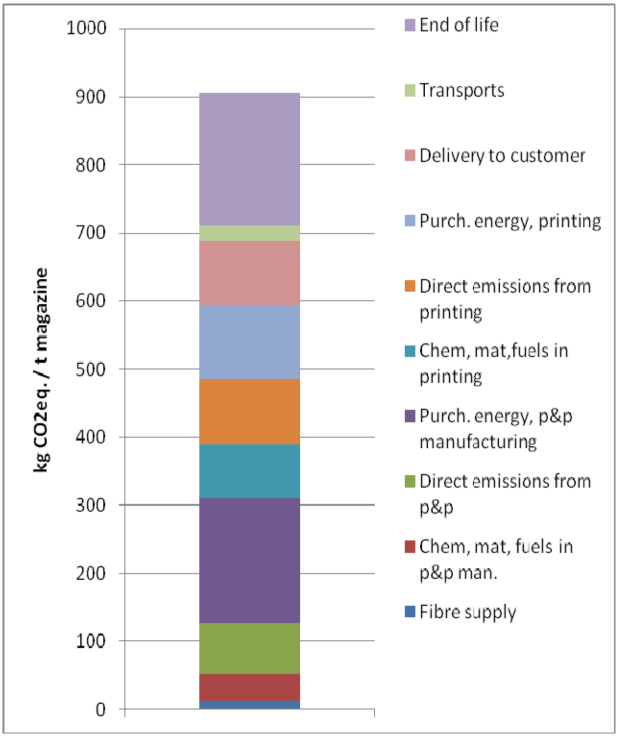


Figure 31. Carbon footprint in the LF high open-loop allocation scenario is 905 kg CO_2eq/ tonne of magazines (air dry tonne).

GHG emissions related to the end of life are mostly methane emissions from magazines disposed to landfill. In this case, a landfill module with higher landfill gas emissions was used and therefore the emissions from landfill have a sizeable contribution to the carbon footprint even though it is assumed that only 16% of magazines end up in a landfill. Some greenhouse gas emissions originate directly from printing houses because propane is burned to produce the heat needed in the printing process.

Instead of propane, natural gas could be used as a fuel in HSWO printing. The CO_2 emission factor of natural gas is 15% lower (55 kgCO_2/GJ) than that of propane, 65 kgCO_2/GJ (Statistics Finland 2010). If there is no difference in the combustion efficiency (i.e. fuel to energy ratio) in natural gas combustion technology compared to propane combustion, then the direct emissions from printing would be reduced by approximately 15%.

Figure 32 shows the percentage contribution of each life cycle stage to the carbon footprint. The biggest share (21%) of the greenhouse gas emissions originates from landfills. 20% of the emissions are generated by the production of the purchased electricity that is used in paper mills. Fossil fuel combustion at pulp and paper mills (direct emissions) contributes 8% of the total greenhouse gas emissions. Printing in total (direct emissions from printing, production of purchased electricity and raw material manufacturing) accounts for 32% of the total carbon footprint.

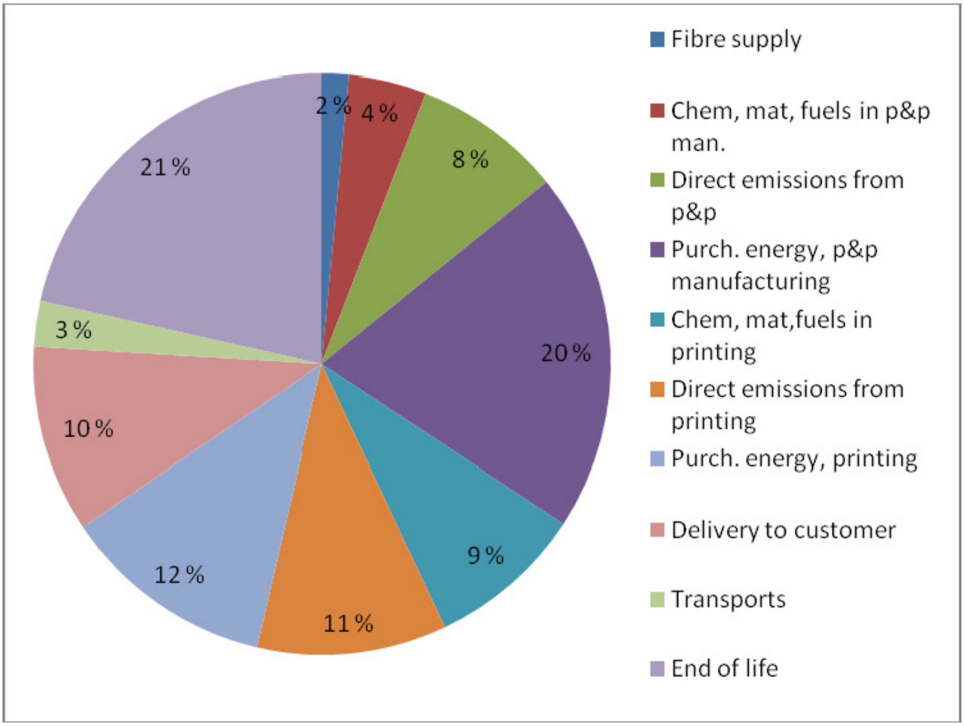


Figure 32. Carbon footprint of a magazine in the LF high open-loop allocation scenario divided into life cycle stages.

Carbon footprints were calculated for both a single magazine and a yearly subscription. In order to cover different-sized magazines, two magazines were studied, one weighing 170 g (56 pages) and the other 250 g (86 pages). Both of the magazines were assumed to be published on a weekly basis, with a total of 48 issues per year. In addition, the contribution of plastic wrapping (LDPE) was studied. The carbon footprint results are summarized in Table 18.

If the carbon footprint of one magazine in the basic case is about 260–380 g CO_2eq, the LDPE wrapping around the product would add 20 g of CO_2 equivalents to the amount, increasing it by 5–8%. If all of the magazines delivered under yearly subscriptions were wrapped in LDPE plastic, this would add about 1 kg CO_2eq to their carbon footprint.

Table 18. Carbon footprints for magazines with different weights (170 g and 250 g) and for a yearly subscription of 48 issues. Scenarios from left to right: 1) basic case with higher landfill emissions, 2) basic case with lower landfill emissions, 3) higher landfill emissions and green grid electricity in printing, 4) higher landfill emissions and open-loop allocation of recyclable fibre, 5) higher landfill emissions and avoided emissions due to production of recyclable fibre.

	LF high	**LF low**	**LF high, green**	**LF high, allocation**	**LF high, avoided emissions**
Carbon footprint of one tonne of magazines	1488 kg	1312 kg	1380 kg	905 kg	1382 kg
Carbon footprint of one issue (170 g, 56pages)	0.253 kg	0.223 kg	0.235 kg	0.154 kg	0.235 kg
Carbon footprint of yearly subscription (48 issues)	12 kg	11 kg	11 kg	7 kg	11 kg
Carbon footprint of one issue (250 g, 86pages)	0.372 kg	0.328 kg	0.345 kg	0.226 kg	0.345 kg
Carbon footprint of yearly subscription (48 issues)	18 kg	16 kg	17 kg	11 kg	17 kg

6.6 Life cycle impact assessment results

The life cycle inventory data of the magazine life cycle was interpreted with the ReCiPe life cycle impact assessment (LCIA) method. The methodology is described in Chapter 2.1.4. LCIA was conducted for the following scenarios:

- basic case with higher GHG emissions from papers disposed to landfill (LF high)
- basic case with lower GHG emissions from papers disposed to landfill (LF low)
- open-loop allocation of recycled fibre and higher GHG emissions from papers disposed to landfill (LF high allocation)
- avoided emissions due to system expansion and higher GHG emissions from paper disposed to landfill (LF high, avoided emissions).

The LCIA method assesses the potential environmental problems caused by the inventoried emissions and use of resources. Environmental problems are called impact categories. In the magazine case, seven impact categories were included in the basic assessment, namely climate change, terrestrial acidification, freshwater eutrophication, photochemical oxidant formation, particulate matter formation, mineral resource depletion and fossil resource depletion. In addition, printing operations were assessed separately, paying attention especially to human toxicity, terrestrial ecotoxicity and freshwater ecotoxicity impacts. See Chapter 2.1.4 for a description of the impact categories.

In the LCIA, normalization was performed in order to enable the comparison of the results for different impact categories against each other. Normalization has been performed against the impacts caused by one European inhabitant during one year. The normalized results mean that if the climate change impact of the pulp and paper phase (for one tonne of magazines) were to be equal to the climate change impact of one European during one year, the length of this impact column would be one.[6] More importantly, however, the figures give an overall picture of the potential environmental impacts caused by the magazine life cycle. Comparisons should be done between the different life cycle phases, pointing out the phases that are significant to the overall environmental performance of the magazine and identifying the development needs.

To study the significance of the assumptions made in the life cycle inventory, several scenarios and sensitivity analyses were calculated for magazines. The LCIA was performed for two basic magazine scenarios, LF low and LF high (Chapter 6.1). In order to study the impact of the large amount of recycled fibre, different allocation methods were applied for the LF high scenario (LF high, allocation and LF high, avoided emissions).

The scenarios are compared in Figure 33. The difference between the LF high and LF low scenarios is that the climate change impact is smaller in the latter due to the lower methane emissions from waste paper landfilling. However, a methodological comparison between allocating emissions and avoiding emissions, as described in Chapter 6.1.1.2, shows a bigger difference to the overall results. Allocating part of the emission load to the recycled fibre leaving the system decreases the amount of paper a printing house needs to produce one tonne of magazines. Thus all impacts generated in pulp and paper production and all the preceding life cycle phases are reduced.

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[6] In Europe, the average consumption of paper products is approx. 155 kg per person in one year. An average Finnish person consumes approx. 230–240 kg of paper products per year (Finnish Forest Industries Federation 2010). In the case study, one yearly subscription of magazines was assumed to weigh 8–12 kg depending on the size of the product.

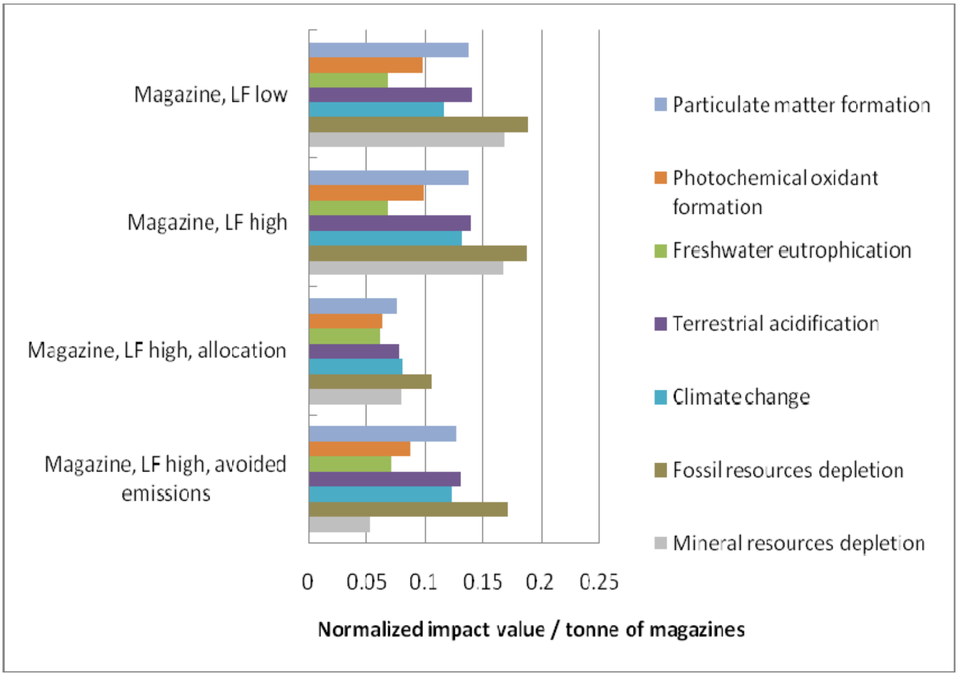

Figure 33. Comparison of life cycle impact assessment results for one tonne of magazines in different scenarios: LF low, LF high, LF high allocation and LF high avoided emissions. Environmental impact of one European inhabitant per year = 1. One yearly subscription to a magazine is assumed to weigh 8–12 kg.

In the avoided emissions (system expansion) method, it is assumed that recycled fibre is used in newsprint manufacturing, which means that the production of thermomechanical pulp (TMP) is avoided. At an integrated plant, the production of pulp and paper and the energy production and need for these processes are interlinked in a highly optimized way. The TMP process consumes electricity but produces heat and the heat is utilized efficiently at the plant. When TMP is not produced (i.e. when de-inked pulp is used), the need for electricity decreases, which is reflected in the lower mineral resources depletion impact in LF high, avoided emissions scenario compared to LF high (Figure 33). At the same time, however, the need for heat increases. Altogether this means that although avoiding TMP production with the use of recycled fibre to some extent reduces environmental impacts in all impact categories, there is no great difference between LF high and LF high, avoided emissions.

It should be kept in mind, however, that recycling saves virgin wood and this saved wood can either be left in the woods where it acts as a carbon sink or used for other purposes such as energy production. This biobased energy can in turn replace fossil-based energy. Altogether this means that the consequences of paper recycling extend to systems outside of the product system modelled here, and thus the savings on emissions and impacts achieved by paper recycling can be much higher than our calculations reveal.

In this case study, the scenario with open-loop allocation and higher emissions from the landfill (LF high, allocation) was considered to be the most relevant one. The LCIA results for the magazine case, "the LF high, allocation scenario", are very similar to the results of the newspaper case. The pulp and paper production, printing and transport phases of the life cycle are responsible for the majority of impacts potentially produced over the magazine life cycle (Figure 34 and Figure 35).

The fibre supply phase has little impact compared to the other phases. The end-of-life phase may have a significant contribution to the climate change impacts, assuming a high paper degradation rate and low landfill gas collection rate (LF high).

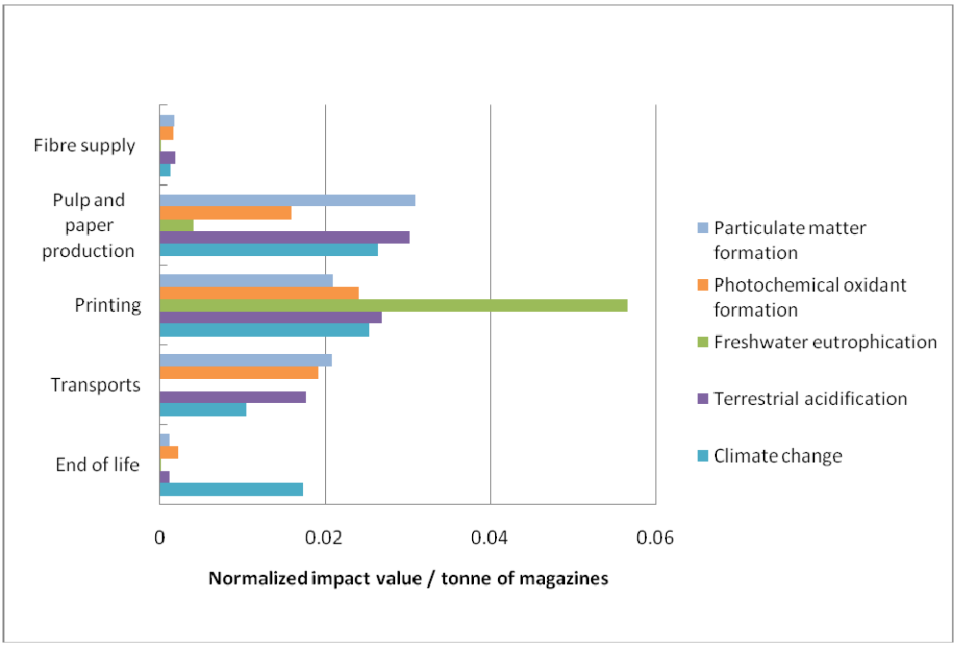

Figure 34. Results of the life cycle environmental impact assessment for one tonne of magazines (LF high, allocation scenario). Environmental impact of one European inhabitant per year = 1. One yearly magazine subscription is assumed to weigh 8–12 kg.

The majority of the impacts in the categories climate change, terrestrial acidification and particulate matter formation are due to energy and fuel use in the system. Climate change impacts are caused by greenhouse gas emissions, mainly CO_2. Acidification is mainly caused by sulphur and nitrogen oxide emissions, which also have a role in particulate formation. Most of the particulates originate, however, directly from the emissions of industrial activities, energy production and traffic. Small particulates can penetrate deep into the lungs and cause respiratory disorders.

Freshwater eutrophication impacts are caused by the phosphorus emissions from pulp and paper production and the printing ink manufacturing chain. Eutrophication leads to changes in species, to algae blooms and to excess shoreline vegetation. The photochemical oxidant formation impacts are mostly due to nitrogen oxide emissions produced by heat and power production and transportation vehicles. Methane, ammonia and carbon monoxide also have the potential of causing photochemical oxidant formation. Ozone and other photo-oxidants cause breathing problems, damage to plant leaves and reduced grain harvests.

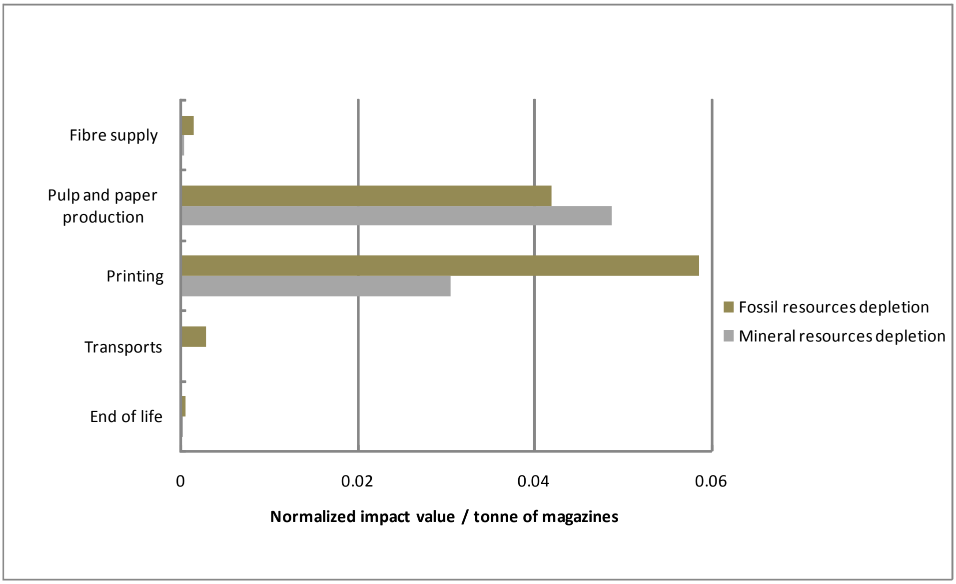

Figure 35. Results of life cycle impact assessment of resource depletion for one tonne of magazines (LF high, allocation scenario). Environmental impact of one European inhabitant per year = 1)

Allocating part of the emission load to the recycled fibre leaving the system reduces all impacts generated in pulp and paper production and the preceding life cycle phases. The influence of allocation can be seen when considering the potential impacts in the resources depletion categories (both fossil and mineral) (Figure 35). The resources depletion impacts originating from the pulp and paper production phase and its energy use are reduced to the same level as the impacts from the printing phase.

The depletion impact is assessed by comparing the magnitude of use against the known reserves. The mineral resources depletion impact is almost solely caused by uranium use originating in the use of grid electricity where the share of nuclear power is 28% (see Appendix C).

The origins of the impacts can be revealed more precisely by taking a closer look at the life cycle phases of pulp and paper production (Figure 36) and printing (Figure 37). In pulp and paper production, four phases can be separated further: direct emissions from mills, production of purchased energy (grid electricity and heat), production of chemicals, materials and fuels and fibre supply (Figure 36).

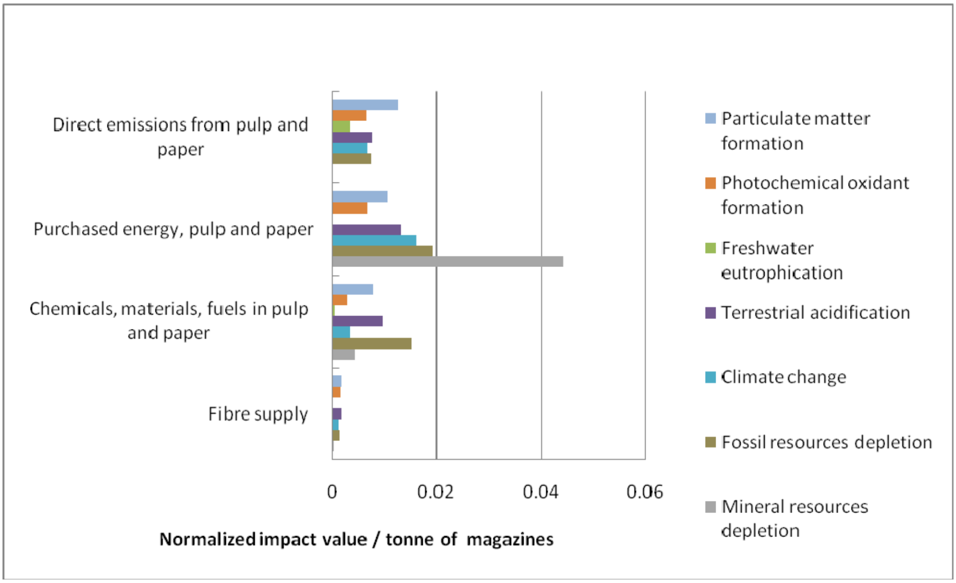

Figure 36. Life cycle impact assessment results for the pulp and paper production phase for one tonne of magazines (LF high, allocation scenario). Environmental impact of one European inhabitant per year = 1.

Most impacts originate in the use of purchased energy and are caused by fuel and energy use in pulp and paper production. The majority of the impacts in the life cycle phase “direct emissions from pulp and paper” are caused by the power production facility at the site and originate in energy use. The third life cycle phase included in pulp and paper production is chemicals, materials and fuels manufacturing and acquisition, in which fuels also play a major role, e.g. in the impacts of resources depletion. The freshwater eutrophication impacts of pulp and paper manufacturing are quite low and are due to phosphorus emissions to water from pulp and paper mills.

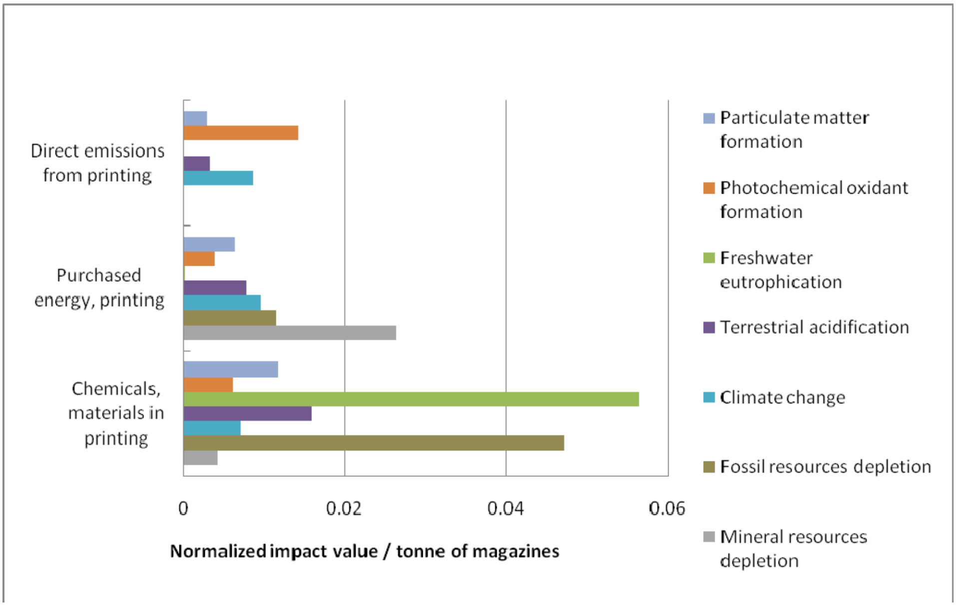

Figure 37. Life cycle impact assessment results for the printing phase for one tonne of magazines (LF high, allocation scenario). The printing phase is divided into three phases. Environmental impact of one European inhabitant per year = 1.

The printing phase can be divided into three life cycle phases (Figure 37). As in pulp and paper production, most of the impacts are due to energy and fuel use. The freshwater eutrophication impacts of chemicals and materials manufacturing and acquisition originate from phosphorus emissions to water from the manufacturing chain of the partly biobased printing ink used in the product system. The fossil resources depletion impacts in the phase “chemicals, materials and fuels in printing” are almost solely caused by crude oil consumption in the printing chemicals manufacturing chains (printing colour, propane, isopropanol).

In addition to the impact assessments reported above, printing operations were assessed separately, paying attention especially to human toxicity, terrestrial ecotoxicity and freshwater ecotoxicity impacts. The toxicity assessment could not be carried out for the whole product system due to deficiencies in the data, especially with respect to the manufacturing and acquisition of chemicals and materials used in pulp and paper production. The toxicity assessment gave indications of high potential for both human toxicity impacts and terrestrial and freshwater ecotoxicity impacts from the production chains of the chemicals used in printing. Most of the human toxicity and freshwater ecotoxicity impacts are caused by metal emissions to air, water and soil. Metal emissions, such as nickel, zinc, vanadium, arsenic, cobalt, originate from the propane and isopropanol manufacturing chains. Terrestrial ecotoxicity is mostly caused by herbicide and insecticide emissions that originate from the partly biobased printing ink manufacturing chain.

One aspect not included in the LCIA is the potential mineral resources depletion impact from using limestone in the production chain for pigments. Use of limestone is currently not included in the impact category mineral resources depletion, even though the emissions from mining and manufacturing are considered in the calculations. This is due to limited data related to availability of mineral resources on earth. The paper used for magazines has a high share of pigments (35%), which are produced from materials such as limestone.[7] The production of 1 kg of pigment requires 1.5 kg of limestone. In 2002 the overall use of limestone and dolomite limestone in Finland was 5659 Mkg, of which the pulp and paper industry used 388 Mkg, approximately 7% (Seppälä et al. 2009).

6.7 Conclusions and discussion

In the case study, the potential environmental impacts of a magazine were evaluated by conducting a life cycle inventory, carbon footprint calculation and life cycle impact assessment. One of the interests of the study was the contribution of different phases of the life cycle to the overall environmental impact caused by the value chain. As a consequence, the results were reported according to life cycle stages.

[7] Limestone is used for the production of $CaCO_3$. Another typical pigment used for LWC paper manufacturing is kaoline.

The impacts of different allocation methods were studied in the magazine case. ISO 14040-44 standards recommend the use of system expansion to avoid allocation, but also present open-loop allocation as a possible allocation method for recyclable products, and hence both of the methods were applied in the magazine case.

The results indicate that the choice of allocation for recyclable fibre has a remarkable impact on the results derived from the study. Open-loop allocation that removes part of the environmental load of paper manufacturing from the studied system clearly leads to the smallest emissions. This is because part of the environmental burden from the manufacturing of recycled fibre is moved to the other product, using the raw material as an input in another product system. This is a calculatory example that highlights the potential benefits provided by recyclability. For example, the carbon footprint calculated using open-loop allocation was 40% smaller than in the basic case, in which cut-off allocation was applied and no benefits from the production of recyclable fibre were obtained.

On the other hand, if system expansion is done, the credits from recycling are not that remarkable due to avoided heat production in TMP manufacturing. The carbon footprint in the avoided emissions scenario was 7% smaller than in the basic case. The result of the avoided emissions scenario is of course dependent on the assumed use of the recycled fibre. In this case, it was assumed that the production of TMP from virgin fibre in newsprint manufacturing would be avoided. This is a plausible scenario in Finland, but other possibilities exist as well.

System boundaries also have a strong influence on the LCA results. The positive impacts of recycling are not always easy to assess extensively. Paper recycling saves virgin wood and this saved wood can either be left in the woods where it acts as a carbon sink or used for other purposes such as energy production. This biobased energy can in turn replace fossil-based energy. Altogether this means that the consequences of paper recycling extend to systems outside of the product system modelled here, and thus the savings on emissions and impacts achieved by paper recycling can be much higher than our calculations reveal.

In the case study, the LF high scenario with open-loop allocation was selected for further study. Based on the LCI results, paper manufacturing (incl. fibre supply, direct emissions from pulp and paper mills, raw material manufacturing and purchased electricity) makes the biggest contribution to SO_2 and TSP emissions to air, 50–60%. Most of the VOC emissions come from printing houses (~70%) and most of the NO_x emissions from all transport including delivery to customer (42%) and paper manufacturing (35%). The printing phase (incl. chemicals, materials and fuels used in printing, direct emissions from printing and purchased energy to printing) contributes 21% of total NOx emissions, 42% of total SO_2 emissions and about 24% of the total TSP emissions. Pulp and paper mills and manufacturing of the printing inks are the biggest contributor to studied water emissions.

The carbon footprint of the magazine in the LF high scenario with open-loop allocation is 905 kg CO_2eq and 1490 kg CO_2eq without allocation. The LF high scenario with no allocation was compared to i) a scenario with lower GHG emissions from landfill and to ii) a scenario with green electricity. If a landfill with higher gas collection efficiency and lower landfill gas emissions is considered, the carbon footprint of one tonne of magazines would be 1351 kg CO_2eq, about 9% smaller than in a landfill with higher emissions. A green electricity option for printing houses would in turn decrease the carbon footprint by 5% (being 1418 kg CO_2eq).

A typical print run of the studied magazines is between 70 000 and 130 000 copies. 100 000 copies of a magazine weighing 170 g equal 17 tonnes of print products in this case study. The GHG emissions (covering the whole life cycle) of this print run amount to approximately 15 000 t CO_2eq (in the case of open-loop allocation). If the weight of one magazine is 250 g, the print run equals 25 tonnes of print products and the GHG emissions of this print run are about 23 000 t CO_2eq. These emissions are equivalent to the yearly GHG emissions from the electricity use of three typical Finnish houses with electrical heating or 24 Finnish flats with district heating[8]. On the other hand, the GHG emissions per one 170 g magazine are about 150–250 g CO_2eq. These emissions equal the GHG emissions caused by driving a car for about 0.9–1.5 km[9] or the electricity used in watching a modern TV for about 4–10 hours in Finland[10]. It should be noted that manufacturing, electronic transmission of programmes and TV disposal and recycling are excluded from the numbers.

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[8] An average 120 m^2 Finnish house for four persons (with electrical heating) consumes 18 MWh of electricity per year. An average 75 m^2 Finnish flat for three persons in an apartment building (with district heating) consumes 2.6 MWh of electricity per year. (Adato Energia 2008, Fortum 2010). The emission factor for Finnish electricity from grid is 250 kg CO_2eq/MWh.

[9] A new passenger car emits on average 164 g CO_2eq/km (lipasto.vtt.fi).

[10] A modern 32–37'' LCD TV set consumes 0.15 kWh_e/h (Helsingin Energia 2010). This is the predominant technology in Finnish homes now and in the near future (Adato Energia 2008). The emission factor for Finnish electricity from grid is 250 kg CO_2eq/MWh.

Based on the LCIA results, the potential contribution of the magazine product system to environmental impacts is mostly connected to the energy and fuels used in different life cycle phases. The use of purchased energy plays the greatest role, both in pulp and paper production and in printing. This underlines the importance of improving energy efficiency in all stages of the life cycle to reduce the environmental impacts created.

The assessment of the potential toxicity impacts of printing operations indicated high potential for both human toxicity impacts and terrestrial and freshwater ecotoxicity impacts from the production chains of the chemicals used in printing. Most of the toxicity impacts were due to metal emissions. High terrestrial ecotoxicity potential was also observed from herbicide and insecticide emissions originating in the production chain of printing colours. This, together with the observation that printing ink manufacturing may also cause high eutrophication impacts, stresses the need to closely study the overall impacts of mineral versus biobased materials. It is noteworthy that the toxicity assessment only partly covered the magazine life cycle due to data gaps, especially with respect to the chemicals and materials used in pulp and paper production.

It must be kept in mind, however, that the toxicity and ecotoxicity assessment in the LCIA framework is still under development. There are major uncertainties connected to the toxicity impacts of metals in particular. Metals form different types of compounds in different environmental conditions and the toxicity of compounds varies. In the LCIA, our knowledge of the environmental conditions in which metal emissions occur is not detailed enough and thus we do not know what types of compounds the metals form.

In addition to the uncertainties in the toxicity impacts assessment, the LCIA does not cover all environmental impacts potentially caused by the magazine life cycle. There are methodological deficiencies also in assessing, for example, the land use impacts in terms of loss of biodiversity and recreational values and degradation of landscapes and in assessing the impacts of odour and noise.

7. Life cycle assessment and carbon footprint of an electrophotography printed photobook

Chapter 7 presents the results of an LCA and carbon footprint case study for a digitally printed photobook, printed with electrophotography. It is assumed that the product is manufactured and read in Finland. The consumer designs the photobook and provides the content for it.

Due to the popularity of digital cameras, people are taking more pictures than ever. The pictures are easily accessible in photobooks, the modern version of photo albums, which enable people to create their own designs. Photobooks generated more than 400 million euros in sales in 2008 based on the median amount spent of about 50 euros. In the global market, more than 60 million photobooks will be produced in 2013 (Pira 2008). The case product is an example of print-on-demand in which the customer orders only one or few copies of the product. As a consequence, each product has a variable content.

During the past few years, the popularity of electrophotography has grown and the pace of technological development has been fast. Electrophotography is used for the economical production of individual products or very short print runs. It is a slow process run by small printing presses. This process is widespread and each printing house can have several electrophotography presses. The method is sometimes abbreviated to EP. The term laser printing is also used. Typical print runs are between 1 copy and 300 copies.

Electrophotography is a non-impact printing method where the image is made from digital data individually for each page on the photoconductor drum. The colorant (toner) is transferred from the photoconductor drum to the substrate with an electric field and without contact. The toner is fixed to the substrate with heat and pressure. The substrate can be either sheets or web. The print quality achieved with EP is usually very high.

The toners used in electrophotography are powders with a small particle size. Liquid toners are used in some presses. Small amounts of silicon oil are used in the process to finalize the product. Electrophotography is a digital printing method, so no transfer plates need to be recycled.

The surface of the photobook cover is coated fine paper, which is very high-quality printing paper made from bleached chemical pulp. The term woodfree paper is also used. In chemical pulping, wood chips and chemicals are combined in digesters where heat and the chemicals break down the lignin to separate the cellulose fibres from each other without seriously degrading them. The kraft process is the dominant chemical pulping method. Coating the paper gives it a smooth and even surface and enables very high print quality. The clay and calcium carbonate ($CaCO_3$) coating is usually made with two layers and the top coating is done as blade coating. The pigment content of coated fine paper can be higher than the fibre content when weight is considered. The board for the photobook cover is grey board, which is made from recycled paper. The waste paper is not bleached during the board-making process. The board has strong stock sizing, making the board very tough and yet flexible.

The inner sheets and end paper of the photobook are made from uncoated fine paper, which is high-quality printing paper made from bleached chemical pulp. The term uncoated woodfree paper is also used. The surface is usually sized to gain good surface strength and water resistance. Pigments are used in the base paper to achieve better whiteness and opacity. The paper is machine calendered to obtain the preferred surface properties.

7.1 Case definition

The goal of the case study was to examine the environmental impacts of a typical digitally printed photobook (photobook). The case study does not present any specific Finnish electrophotographic printed photobook. Rather, it provides an example of a photobook that could be manufactured in Finland. The basic assumptions of the case study were defined together with paper and printing industry representatives.

The scope of the study was cradle to customer, excluding end of life from examination. It could be argued that the approach is cradle to use, because using the photo book does not consume energy. The decision to limit the study to the cradle-to-customer approach only was made because there is no data available concerning the end of life of photobooks. This is partly due to the fact that the product group is fairly new. Some assumptions could have been made, but since there is remarkable uncertainty associated with the decomposition of photobooks and the deinkability of digitally printed products, the uncertainty of end-of-life calculations would have grown significantly. On the other hand, it can be argued that photobooks are stored for a longer time and consumers rarely face the decision of whether to dispose of their photobooks.

The functional unit used in the case study was 1000 kg of photobooks. The carbon footprint was also calculated for a photobook weighing 500 g and another weighing 800 g (mass based). Table 19 summarizes the case study assumptions for digitally printed photobooks.

Table 19. Case study assumptions for an electrophotography printed photobook.

Print product	Digitally printed photobook, hardcover, glue bound, size A4
Printing	Electrophotography (EP), 4-colour printed
Paper	Cover: 1300 gsm board (100 % defibered pulp from board and unbleached paper) + 150 gsm coated fine paper + laminate Inner sheets: 150 gsm coated fine paper (11% pine kraft pulp, 34% birch kraft pulp, 50% pigments, 5% binders) End papers: 150 gsm uncoated fine paper (21% pine kraft pulp, 50% birch kraft pulp, 25% fillers, 4% binders) Board for back: excluded from the calculations due to negligible contribution
Weight and dryness	500 g (64 pages) and 800 g (128 pages)/book, dryness 96%
Packaging	Corrugated board box 120 g, plastic wrapping 14 g
Geographical aspects	Paper production, printing and delivery in Finland
Distribution	Delivery to home
Storage at home	50 years

Figure 38 shows the system boundary of the studied system. A cradle-to-customer approach was applied, meaning that the life cycle was studied from raw material extraction until the customer receives the photobook in the mail. The paper mills were assumed to be integrated with pulp mills. Data on paper manufacturing was derived mainly from the KCL Ecodata database.

LCI data concerning the printing phase was collected from four Finnish printing houses. Additional information was also received from printing press manufacturers and toner manufacturers. Maculature percentage in photobook manufacturing was estimated to be 17%.

Data on toner production was derived from the Ecoinvent 2.2. database and the data mainly concerns toner production for office laser jets. However, a component manufacturer verified the data, and thus it was assumed that the data is accurate enough to be used for industrial digital printing too. Toner production includes the raw materials of toner and the actual manufacture of toner powder. The circulation and refilling of empty cartridges were excluded from this study due to lack of data, but it should be noted that cartridge circulation may lead to increased environmental impacts and emissions.

It is assumed that digitally printed photobooks are distributed by mailing them to the homes of customers. Data on the emissions of home delivery was sourced from a Finnish logistics company. The production of photobook content (performed by the consumer at home) was not included in the study. Data sources and data age are presented in detail in Appendix E.

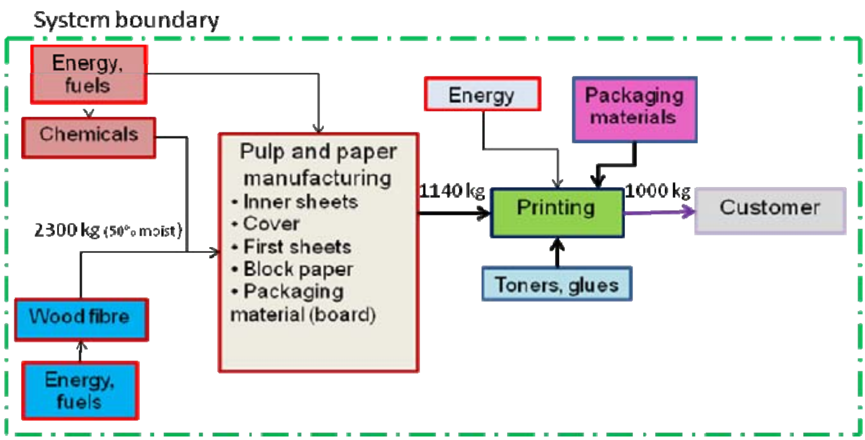

Figure 38. System boundary in the photobook case with fibre flow (moist).

In this case study, the studied system is divided into different book components because the final product consists of several materials. The following table (Table 20) presents the studied processes and life cycle phases divided into different photobook components. Printing and transportation are examined separately.

Part of the results of this case study were presented in the NIP26 conference in August 2010 and published in the proceedings (Kariniemi et al 2010).

Table 20. Life cycle of a photobook is divided into different photobook components.

Life cycle stage	**More detailed**	**Included processes / notes**
Inner sheets	Woodfree, coated, 150 gsm, 50% pigments, manufactured in Finland	Fibre supply, pulp and paper manufacturing, chemical and other raw material manufacturing, fuels and energy, wood, chemical and fuel transportation.
Cover	Cover sheet: Woodfree, coated, 150 gsm, 50% pigments, manufactured in Finland Board for cover: recycled board, 1300 gsm, manufactured in Europe	Fibre supply, pulp and paper manufacturing, chemical and other raw material manufacturing, fuels and energy, wood, chemical and fuel transportation.
End papers	Woodfree, uncoated, 150 gsm, manufactured in Finland	Fibre supply, pulp and paper manufacturing, chemical and other raw material manufacturing, fuels and energy, wood, chemical and fuel transportation.
Block paper	Woodfree, uncoated, 80 gsm, manufactured in Finland	Fibre supply, pulp and paper manufacturing, chemical and other raw material manufacturing, fuels and energy, wood, chemical and fuel transportation. Block paper is used in printing to divide the printing runs.
Direct emissions from printing	Direct emissions from printing, e.g. from fossil fuel combustion	There are no direct emissions from the EP printing site, but it is shown in the figures to guarantee the transparency of reporting.
Purchased energy in printing	Emissions associated with purchased electricity in printing	Production of grid electricity.
Chemicals, materials and fuels in printing	Toner Glue	Manufacturing of toner and glues needed to produce a photobook.
Box	Corrugated board, including recycled fibre, manufactured in Finland	Fibre supply, pulp and paper manufacturing, chemical and other raw material manufacturing, fuels and energy, wood, chemical and fuel transportation.
Plastic wrapping	LDPE packaging film, manufactured in Europe	LDPE production, transportation to extrusion, extrusion.
Delivery to customer	Delivery to customer	Home delivery.
Other transportation	Other transportation	Paper, toner, glue transportation. Note! Does not include wood or other raw material transportation in paper production since such transportation is included in the respective life cycle stages.

7.2 Life cycle inventory results

The life cycle inventory results presented in this chapter include NOx, SO_2 and TSP emissions to air and COD, Ntot, Ptot, TSS emissions to water. All greenhouse gas emissions are included in the carbon footprint that is reported in Chapter 7.3. The results of the life cycle inventory are presented in detail in Appendix E. Aspects related to solid waste are discussed but not reported in detail due to uncertainty concerning the background data used for solid waste amounts.

7.2.1 Emissions to air

Nitrogen oxides (NOx), sulphur dioxide (SO_2) and total particulate matter (TSP) emissions were included in the inventory (for greenhouse gas emissions, see Chapter 7.3). Figure 39 presents the NOx, SO_2 and TSP emissions and the emission sources.

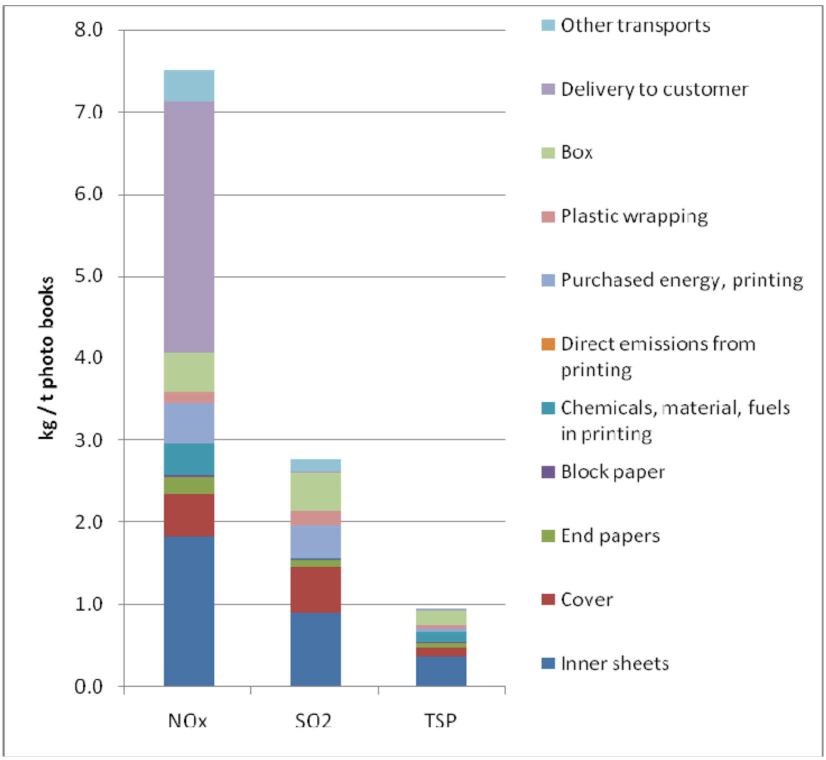

Figure 39. NOx, SO_2 and TSP emissions to air, cradle-to-customer approach [kg / tonne of photobooks].

Figure 39 shows that delivery to home clearly makes the largest contribution to NOx emissions, causing roughly 40% of the emissions. Inner sheet manufacturing has a clear impact on emissions to air too, causing about 25% of the total NOx emissions, 35% of the SO_2 emissions and about 40% of the total TSP emissions. The printing phase (purchased energy for printing, toner and glue manufacturing and block paper manufacturing) contributes about 12% of NOx emissions, 15% of SO_2 emissions and 20% of total TSP emissions.

No direct emissions to air occur from printing houses because the electrophotography printing process does not create VOC emissions. In the EP process, a very small amount of ozone is created at the site, but this was not considered in the study due to its minor impact. Reported air emissions related to the printing phase are caused by the production of purchased energy.

7.2.2 Emissions to water

Chemical oxygen demand (COD), total nitrogen (Ntot), total phosphorus (Ptot), total suspended solids (TSS) and adsorbable organic halogen compounds (AOX) were included in the inventory. The COD figure expresses the amount of organic oxygen-consuming compounds in the wastewater. AOX expresses the amount of chlorine contained in the organic compounds. When released to the water system, nitrogen and phosphorous emissions cause eutrophication. TSS means the amount of solid matter included in the wastewaters.

About 57% of COD emissions originate from woodfree paper production for inner sheets; cover manufacturing (board and woodfree cover sheet) accounts for roughly 17% of this amount and end papers for about 8%. About 16% of COD emissions come from corrugated board box manufacturing. The biggest contributors to Ntot emissions are corrugated board boxes (~40%), inner sheets (~40%) and covers (~11%). In Ptot emissions, the biggest contributors are plastic wrapping (~35%), corrugated board box (~20%) and inner sheets (~22%).

Inner sheets account for about 47% of the total TSS emissions, whereas the cover and toners used in printing both have a share of about 9% of total TSS emissions. AOX emissions come mainly from woodfree paper manufacturing (inner sheets and end papers). The printing phase (purchased energy for printing, toner and glue manufacturing and block paper manufacturing) contributes about 1% of COD emissions, 1% of Ntot emissions, 9% of Ptot emissions and 10% of total TSS emissions. Table 21 presents the total amounts of emissions to water in the studied system.

Table 21. Emissions to water, cradle-to-customer approach [kg / tonne of photobooks].

Emissions to water	**COD**	**Ntot**	**Ptot**	**TSS**	**AOX**
Kg / tonne of photobooks	13.7	0.2	0.03	1.6	0.1

It should be noted that different emissions cause diverse impacts on the environment. These impacts are assessed in life cycle impact assessment phase.

7.2.3 Solid waste

Like all industrial production, the manufacturing of a photobook produces some solid waste. When cradle-to-gate solid waste amounts are calculated, the amount of solid waste produced amounts to 310 kg. Of the total amount, 170 kg (55%) are maculature from printing houses that end up in paper recycling. Most of the solid waste is recyclable or combustable, but small amounts of hazardous waste are produced. The amount of hazardous waste equals about 0.1% of the total waste amount.

In electrophotography printing, empty toner cartridges are returned to the toner manufacturer and refilled. The circulation and refilling of cartridges was excluded from the study. Thus for example the possible amount and handling of the waste toner left in cartridges was not included in the figures. More information about these phases would be required to better evaluate the potential environmental burden related to electrophotography printing. In addition, the deinkability of electrophotography printed products is improving all the time. Both the deinking process and toner composition are being developed further. (See also Chapter 3.2.2.)

The amounts of solid waste involve considerable uncertainty because the completeness of data related to solid waste is poor along the photobook value chain and therefore the amounts of solid waste are not reported in more detail. In general, the recycling rates of different waste fractions in both the paper and printing industries in Finland are relatively high (see, e.g. Finnish Forest Industries Federation 2009; Viluksela et al. 2008).

7.3 Carbon footprint results

Carbon footprint includes the greenhouse gas emissions produced during the life cycle of a product. In the photobook case, the carbon footprint was calculated according to the PAS 2050 guidelines and the carbon stored in the product was included in the study. (For more information about carbon footprints and PAS 2050, see Chapter 2.2. and appendix H.)

The cradle-to-customer carbon footprint of a tonne of photobooks is 2013 kg CO_2eq (Figure 40). The end of life (disposal to landfill, recycling and incineration with energy recovery) was excluded from the study since no information about the disposal of the books after use was available. Inclusion of end-of-life treatment would most probably increase the emissions due to decomposition of paper in landfills. On the other hand, fibres could be recycled and virgin fibre production could be prevented. However, deinkability of (large amounts of) digitally printed paper might require more energy and chemicals compared to traditional deinking processes and thus the benefits from recycling could decrease.

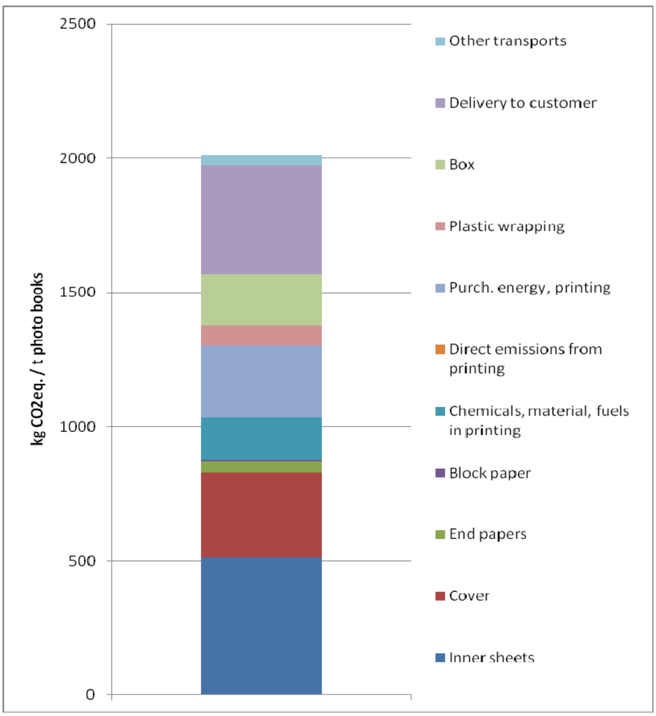

Figure 40. Cradle-to-customer carbon footprint of a photobook [kg CO_2eq/tonne of photobooks].

Figure 41 presents the carbon footprint of a photobook, showing the shares of each component and printing. It can be seen that the paper used in the book has a total share of 44%. Delivery to customer produces roughly 20% of the cradle-to-customer greenhouse gas emissions. The printing phase accounts for about 21% of the total cradle-to-customer greenhouse gas emissions. If the delivery to the customer is excluded and the carbon footprint is calculated until the gate of the printing house (cradle to gate), the total amount of GHGs created is 1610 kg CO_2eq/tonne of photobooks.

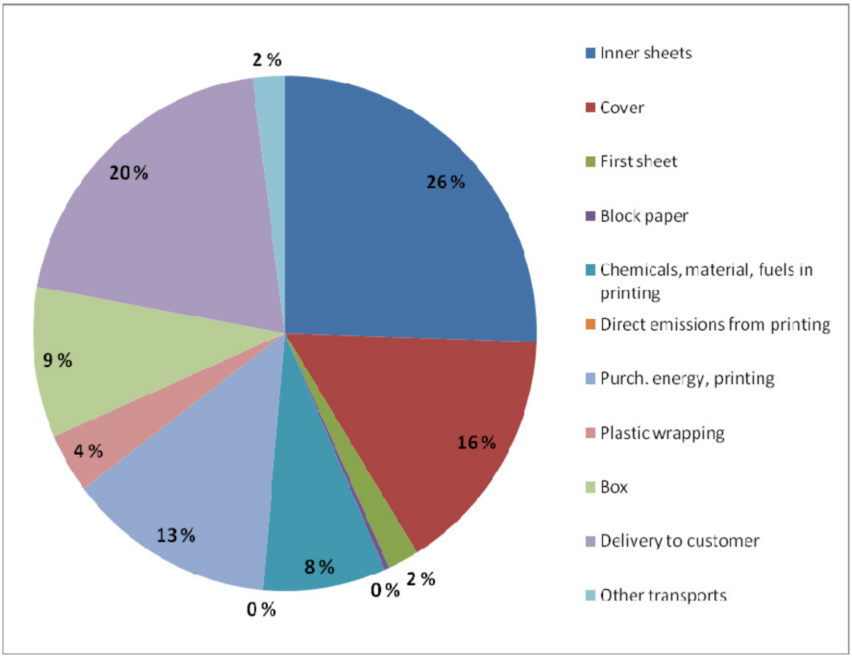

Figure 41. Relative shares of each component of a photobook and the printing phase in the cradle-to-customer carbon footprint.

The previous figure shows that packaging materials (corrugated board and LDPE film) contribute substantially to the carbon footprint of a photobook. This is because every single book is packaged separately and thus the amount of packaging materials used is relatively high. In the following table (Table 22), carbon footprints are presented with and without packaging materials. In addition, carbon footprints of photobooks are presented for two different-sized books: one weighing 500 g (roughly 64 pages) and the other weighing 800 g (roughly 128 pages).

Table 22. Carbon footprint of a photobook with and without packaging materials. Delivery to customer is included in numbers. Carbon footprint was calculated for two photobooks of different weights, 500 g and 800 g. [kg CO_2eq.]

Carbon footprint, cradle to customer	**With packaging material**	**Without packaging material, kg CO_2 eq.**
Total, one tonne of photobooks	2013 kg CO_2eq.	1745 kg CO_2eq.
Total, one photobook, weight 500 g, 64 pages	1.0 kg CO_2eq.	0.870 kg CO_2eq.
Total, one photobook, weight 900 g, 128 pages	1.42 kg CO_2eq.	1.28 kg CO_2eq.

7.3.1 Calculating carbon storage according to PAS2050

As mentioned in Chapter 2.2.1, PAS 2050 allows the impact of carbon storage to be credited from the carbon footprint of a product if "*more than 50% of the mass of carbon (of biogenic origin) in the product remains removed from the atmosphere for one year or more following the production of the product*". In this study, it was assumed that a photobook is kept for 5 years or for 50 years in a bookshelf and the carbon storage is calculated for both lifespans. The calculation of carbon content and carbon storage is presented in Appendix H. The results are shown in Table 23.

Carbon storage in this example is calculated for one tonne of photobooks and for one photobook. Two different assumptions are made concerning the degradation rate of carbon in the book:

- Book is stored for 50 years, after which it is destroyed (e.g. combusted) immediately and the carbon is released back to the atmosphere.
- Book is stored for 5 years, after which the carbon degrades at a rate of 20% per year.

Table 23. Carbon storage and carbon footprints with credited storage, calculated according to PAS 2050 for assumed storage times of 50 years and 5 years. The carbon content of the product is expressed as carbon dioxide (CO_2). For assumptions related to carbon content of product, see appendix H.

	Weight of the photobook	**Unit**	**1 tonne**	**500 g**	**800 g**
	Cradle-to-customer carbon footprint (without packaging)	CO_2eq.	1745 kg	870 g	1280 g
	Carbon content of a photobook	C content as CO_2	1069 kg	530 g	760 g
50 years storage, then 100% degradation	Carbon storage that can be credited from carbon footprint	CO_2	534 kg	260 g	380 g
	Carbon footprint according to PAS 2050	CO_2eq.	1211 kg	610 g	900 g
5 years storage, then 20% degradation/year	Carbon storage that can be credited from carbon footprint	CO_2	75 kg	37 g	53 g
	Carbon footprint according to PAS 2050	CO_2eq.	1670 kg	833 g	1227 g

However, usually the situation is not that straightforward and the carbon in the photobook might be released slowly to the atmosphere (e.g. when degrading in a landfill). If multiple photobooks are studied, some of them are probably stored for 50 years but some of them are stored only for a while and some for even longer than 50 years. The examples in this report illustrate two possible storage scenarios and show that the carbon storage benefit is strongly dependent on the time frame studied.

According to PAS 2050 it could be concluded that the longer carbon is stored in a product, the smaller the carbon footprint of that product. However, it is important to decrease actual emissions and not to rely too much on carbon storage benefits.

7.4 Life cycle impact assessment results

The life cycle inventory data of the photobook life cycle was interpreted with the ReCiPe life cycle impact assessment (LCIA) method. The methodology is described in Chapter 2.1.4. The LCIA method assesses the potential environmental problems caused by the inventoried emissions and use of resources. Environmental problems are called impact categories.

In the photobook case, ten impact categories were included in the assessment, namely climate change, terrestrial acidification, freshwater eutrophication, photochemical oxidant formation, particulate matter formation, mineral resource depletion, fossil resource depletion, human toxicity, terrestrial ecotoxicity and freshwater ecotoxicity impacts. See Chapter 2.1.4 for a description of the impact categories. Due to the extensive use of Ecoinvent data in the life cycle inventory, the LCIA can be carried out on a more extensive group of environmental impact categories than in the newspaper and magazine cases.

The normalized LCIA results for one tonne of photobooks are presented in Figure 42-Figure 46. Normalization is performed in order to enable the comparison of the results for different impact categories against each other. Normalization has been performed against the impacts caused by one European inhabitant during one year. The normalized results mean that if the climate change impact of the transports (for one tonne of magazines) were to be equal to the climate change impact of one European during one year, the length of this impact column would be one[11]. More importantly, however, the figures give an overall picture of the potential environmental impacts caused by the photobook life cycle. Comparisons should be done between the different life cycle phases, pointing out the phases that are significant to the overall environmental performance of a photobook and showing the needs for development.

According to the LCIA results, the life cycle phases "photobook materials", "packaging materials" and "delivery to consumer" are responsible for the majority of impacts potentially produced over the life cycle of a photobook (see Figure 42, Figure 43 and Figure 44). The use of small vehicles in delivering small amounts of photobooks is reflected in the relatively high impacts caused by exhaust gas emissions. Other transport clearly has the least impacts, followed by purchased energy for printing and chemicals, materials and fuels for printing.

[11] In Europe, the average consumption of paper products is approx. 155 kg per person in one year. An average Finnish person consumes approx. 230–240 kg of paper products per year (Finnish Forest Industries Federation 2010). In the case study, one photobook was assumed to weigh 500–800 g. One tonne of photobooks equals about 2000 photobooks.

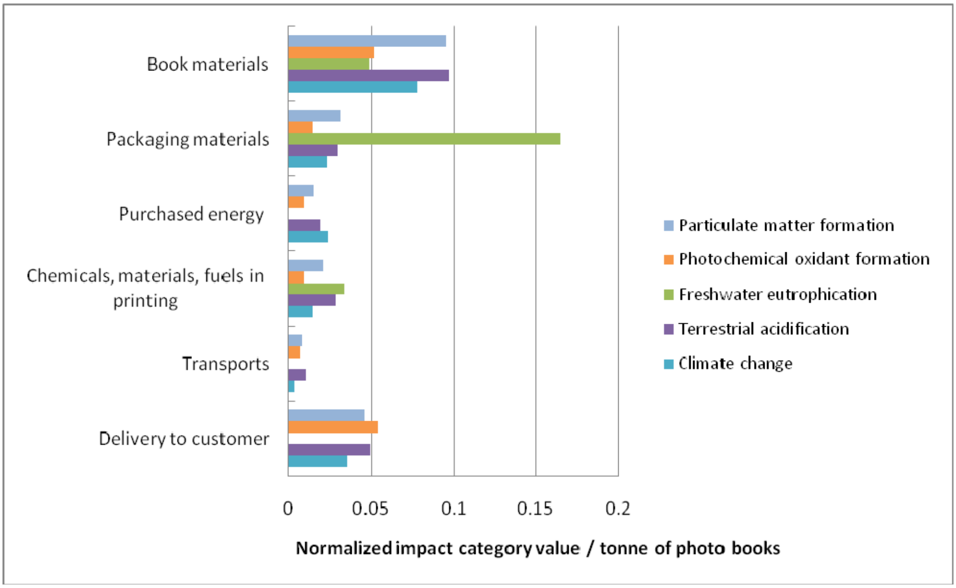

Figure 42. Results of life cycle environmental impact assessment for one tonne of photobooks. Environmental impact of European inhabitant per year = 1. One tonne of photobooks equals 2000 books.

The majority of the impacts in the categories "climate change", "terrestrial acidification" and "particulate matter formation" are due to energy and fuel use in the system. Climate change impacts are caused by greenhouse gas emissions, mainly CO_2. Acidification is mainly caused by sulphur and nitrogen oxide emissions, which also have a role in particulate formation. Most of the particulates originate, however, directly from the emissions of industrial activities, energy production and traffic. Small particulates can penetrate deep into the lungs and cause respiratory disorders.

Freshwater eutrophication impacts are caused by the phosphorus emissions from paper manufacturing and the plastic wrapping manufacturing chain. Eutrophication leads to changes in species, to algae blooms and to excess shoreline vegetation. The photochemical oxidant formation impacts are mostly due to nitrogen oxide emissions produced by heat and power production and transportation vehicles. Methane and carbon monoxide also have the potential of causing photochemical oxidant formation. Ozone and other photo-oxidants cause breathing problems, damage to plant leaves and reduced grain harvests.

Considering the potential impacts in the fossil resources depletion category, energy use in the manufacturing chains of both the photobook materials and the packaging materials and in the printing process is clearly the biggest contributor (Figure 43). The depletion impact is assessed by comparing the magnitude of use against the known reserves. The mineral resources depletion impact is mostly caused by uranium use originating in the use of grid electricity where the share of nuclear power is 28% (see Chapter 4.1.1).

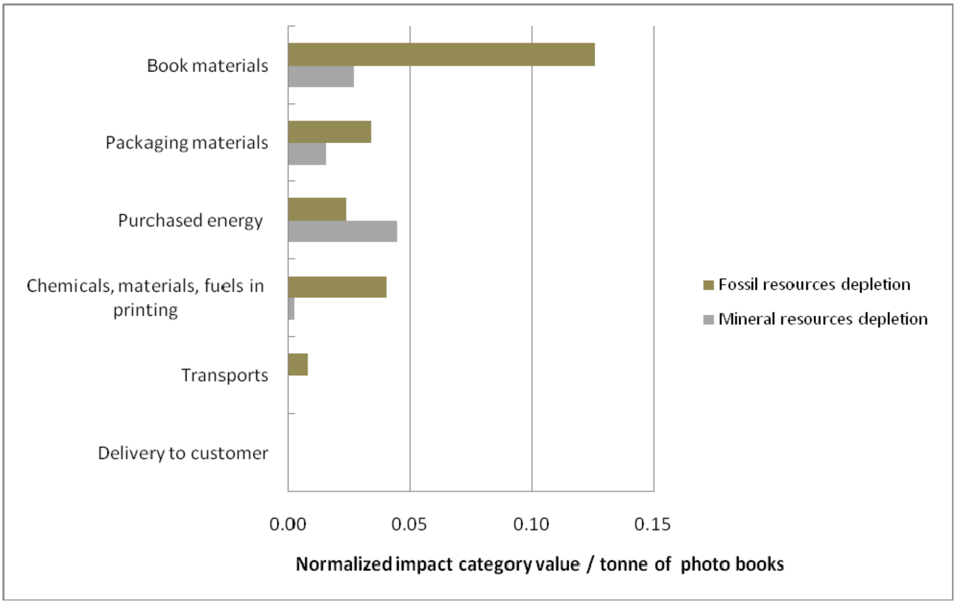

Figure 43. Results of life cycle impact assessment of resource depletion for one tonne of photobooks. Environmental impact of one European inhabitant per year = 1.

Toxicity impacts (Figure 44) to humans as well as the freshwater ecotoxicity impacts are mostly caused by metal emissions to air, water and soil. Emissions of three metals – namely cobalt, nickel and vanadium – to water are responsible for over half of the freshwater ecotoxicity impacts.

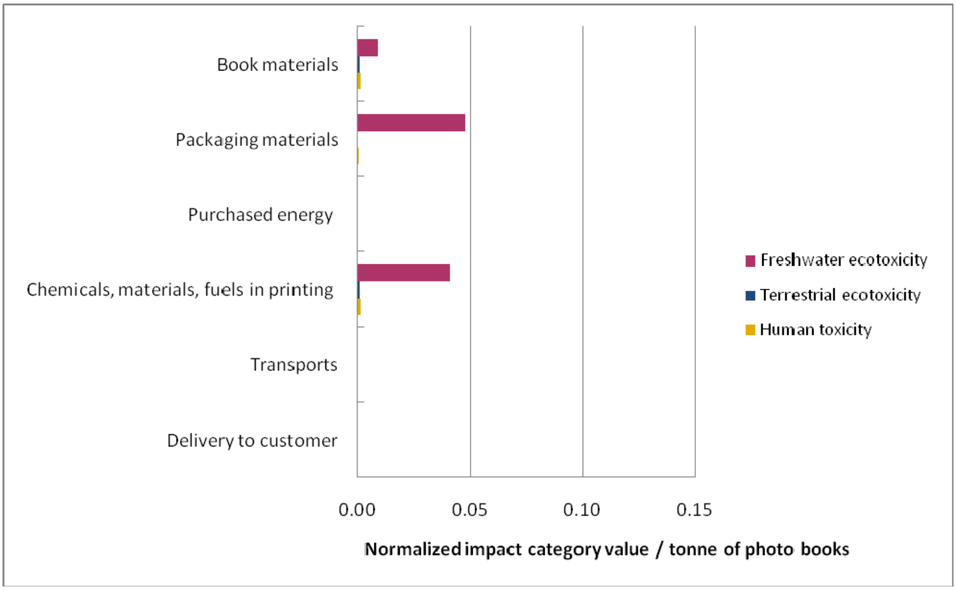

Figure 44. Results of life cycle impact assessment of toxicity for one tonne of photobooks. Environmental impact of one European inhabitant per year = 1.

The origins of the impacts can be revealed more precisely by taking a closer look at the life cycle phases “manufacturing of photobook materials” (Figure 45) and “packaging materials” (Figure 46).

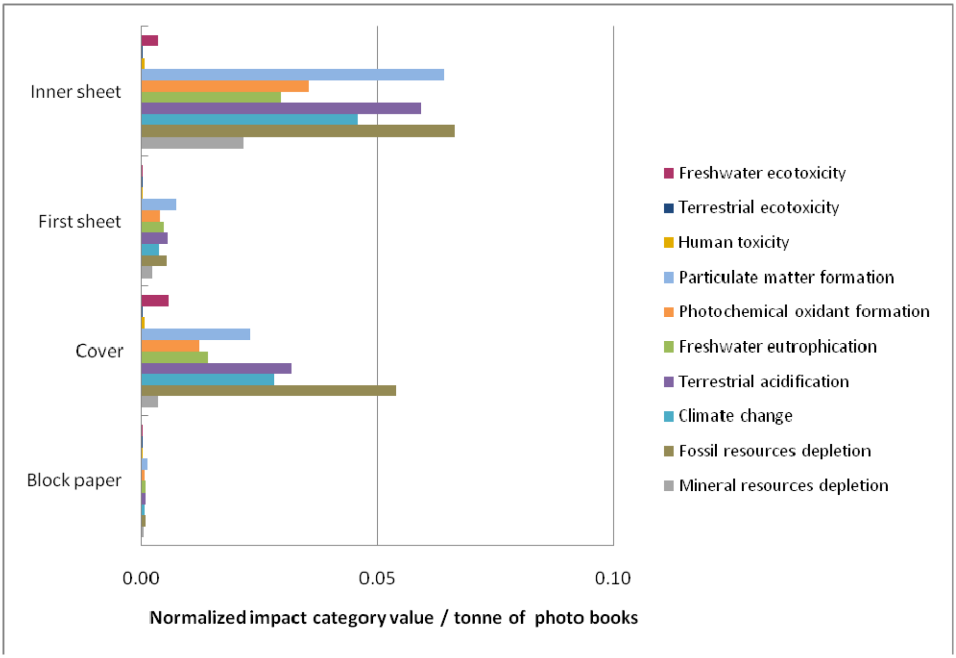

Figure 45. Life cycle impact assessment results for different materials used in the photobook (per one tonne of photobooks). The materials are divided into four material groups (life cycle phases). Environmental impact of one European inhabitant per year = 1.

The materials used for the photobook can be divided into four material groups or life cycle phases: inner sheet, first sheet, cover and block paper. The manufacturing of these different types of materials (paper) for the photobook likewise contributes to the environmental impacts. Due to the differences in the amounts of materials used for each photobook, the overall amounts of the impacts differ as well. The consumption figures are highest for the inner sheet, and thus it also causes the greatest impacts (Figure 45).

The materials used for the packaging can be divided into two life cycle phases: plastic wrapping and corrugated board boxes (Figure 46).

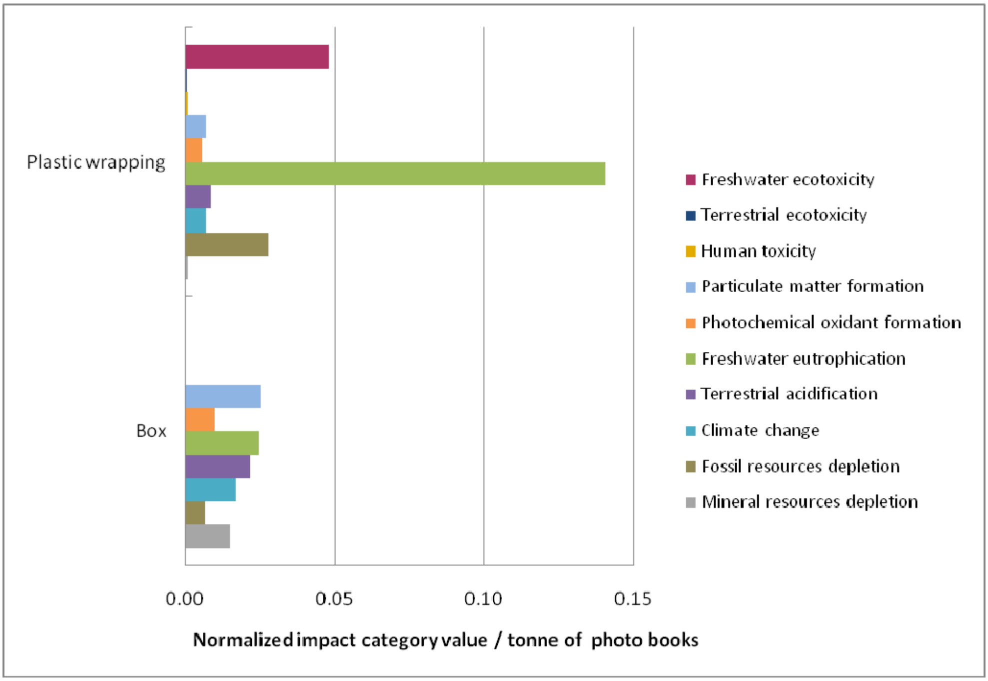

Figure 46. Life cycle impact assessment results for the packaging materials of the photobook (per one tonne of photobooks). Environmental impact of one European inhabitant per year = 1.

The raw materials used for plastics are oil and natural gas, which is reflected in the fossil resources depletion impacts caused by plastic wrapping. The eutrophication impacts from plastic wrapping are due to high phosphorus emissions. Freshwater ecotoxicity impacts from plastic wrapping are mainly caused by metal emissions to water, of which 60% comprise cobalt, nickel and vanadium.

7.5 Conclusions and discussion

In the case study, the potential environmental impacts of an electrophotography printed photobook were evaluated by conducting a life cycle inventory, carbon footprint calculation and life cycle impact assessment. The life cycle of the product was studied from cradle to customer and the end of life was excluded. In the carbon footprint, the carbon stored in the product was calculated according to PAS 2050 for 50 years and 5 years of assumed storage.

In the life cycle inventory, NOx, SO_2 and TSP emissions to air were included. Of the studied life cycle phases, delivery to home has clearly the biggest contribution to NOx emissions, causing roughly 40% of the emissions. The high share of home delivery in both NOx emissions and carbon footprint is related to the use of small vehicles in the delivery phase. Inner sheet manufacturing has a clear impact on emissions to air, too, causing about 25% of the total NOx emissions, 35% of the SO_2 emissions and about 40% of the total TSP emissions. The printing phase (purchased energy for printing, toner and glue manufacturing and block paper manufacturing) contributes about 12% of NOx emissions, 15% of SO_2 emissions and 20% of total TSP emissions.

When considering the studied emissions to water, about 57% of COD emissions, 40% of Ntot emissions, 22% of Ptot emissions, 47% of TSS emissions and most of the AOX emissions originate from woodfree paper production for inner sheets. Inner sheets comprise the bulk of the end product and are the material that is consumed in the greatest quantities. Packaging materials also clearly contribute to emissions to water. The printing phase, on the other hand, has a minor contribution to emissions to water.

The cradle-to-customer carbon footprint of a tonne of photobooks is 2013 kg CO_2eq. One tonne of photobooks equals approximately 2000 books. The GHG emissions per one 500 g photobook amount to about 1000 g CO_2eq and per one 800 g photobook to about 1420 g CO_2eq. The greenhouse gas emissions caused by the manufacturing and delivery of one photobook equal the GHG emissions caused by driving a car for about 6.1–8.7 km[12] or the electricity used in watching a modern TV for about 27–38 hours in Finland[13.] It should be noted that manufacturing, electronic transmission of programmes and TV disposal are excluded from the numbers.

Compared to the carbon footprint of newspaper and magazine presented in earlier chapters, the carbon footprint of photobook is clearly bigger. This can be partly explained by the fact that photobook is a more complex product that includes several materials. Also the single packaging of products contributes to the total environmental impact of the product. However, some level of packaging is a necessary protection that enables the delivery of the product by mail. If a consumer would drive a car to pick up the book from a certain delivery point, the

[12] A new passenger car emits on average 164 g CO_2eq/km (lipasto.vtt.fi).

[13] A modern 32-37'' LCD TV set consumes 0.15 kWh_e/h (Helsingin Energia 2010). This is the predominant technology in Finnish homes now and in the near future (Adato Energia 2008). The emission factor for Finnish electricity from grid is 250 kg CO_2eq/MWh.

occurred GHG emissions could easily exceed the carbon footprint created during the manufacturing of the product.

Another clear difference between the LCA case products – the magazine, newspaper and photobook – is the print production phase. Electrophotography is a fairly new technology and not many studies about the environmental impacts of the method and related raw materials are available. The differences related to the printing process and environmental performance of electrophotography compared to mechanical (offset) printing methods are discussed in Chapter 3.

End of life was excluded from the study due to lack of data related to end use of products. However, on the basis of the other cases, it can be recommended that consumers should not dispose of their photobooks to landfill after use but either recycle or dispose of them to energy recovery. If a photobook is recycled with other household paper waste, its covers should be separated and recycled with board waste and the inner sheets with newspapers and magazines.

The carbon stored in the photobook was calculated according to PAS 2050 guidelines. The assumed storage time was 5 and 50 years. As a conclusion, it can be stated that for paper products, a rather long storage time needs to be expected before considerable benefit or credit is created. By following the principles of PAS 2050, the carbon credit for five-year storage of a photobook is approximately 4% of the total carbon footprint. For 50 years storage, the credit is approximately 30% of the total carbon footprint. The publishing of the ISO 14067 standard for carbon footprint of products will probably determine how the biogenic carbon stored in the products will be handled and presented in carbon footprint calculations in the future (see Chapter 2.2.3). At the time of writing, the development of the standard was still ongoing.

In order to give more precise recommendations concerning end of life, more research is needed, especially with respect to recycling rates and the deinkability of digitally printed products. Concerning the life cycle of electrophotography printed products, additional information would also be needed on the manufacturing of toner used in the printing process and the circulation and refilling process of the empty toner cartridges. This process is handled by the toner manufacturer. Since the market share of electrophotography printed products is expected to grow in the future, it would be important to include information on all relevant life cycle stages in future studies.

The potential contribution of the digitally printed photobook product system to environmental impacts is mostly connected to the manufacturing of the different types of paper and cardboard used for the book. The different fibre materials have similar impact profiles, but the overall amounts of impacts differ according to the different amounts of materials needed for the book. Delivery to consumers also has a very relevant role in the overall impacts. It is thus important to further optimize transport.

It should also be noted that the LCIA does not cover all environmental impacts potentially caused by the photobook life cycle. There are methodological deficiencies in, for example, assessing the land use impacts in terms of loss of biodiversity and recreational values and degradation of landscapes and in assessing the impacts of odour and noise.

8. Carbon footprint of a gravure printed leaflet

Chapter 8 presents the results of a carbon footprint case study for a gravure printed advertisement leaflet. The carbon footprint was calculated based on a life cycle assessment. The case study includes both Finnish and European scenarios for manufacturing and use of the product.

Gravure printing is used for the economical production of long print runs (magazines, catalogues, leaflets). It is a process that employs very fast and wide printing presses. There are few such printing houses compared to offset printing houses and each gravure printing house has 1 to 3 printing machines. The terms gravure, rotogravure and even roto are sometimes used interchangeably. Typical print runs are between 0.5 and 3 million copies. Gravure printing can utilize different types of papers, and the print quality is highly dependent on the substrate used.

Gravure printing is a simple process where the image elements are engraved as small cells into the surface of the printing cylinder. Prior to printing, the entire printing cylinder is flooded with very fluid ink and the excess ink is removed from the non-image area by a doctor blade. The ink is transferred from the cells to the printing substrate by high printing pressure and the help of an electric field. The cylinders are gapless and have a variety of diameters to match the size of the printed product. The preparation of the gravure cylinder is expensive. Basically, this means that gravure printing is economically feasible only in long print runs. The quality of the print can be very high, but depends strongly on the substrate used.

Inks used in publication gravure printing are solvent (toluene) based and they are dried by evaporation. The solvent is recovered and reused in the inking system. The printing cylinders are made from copper and coated with chrome and the valuable metals are recycled.

Supercalendered paper (SC paper) is typically used for rotogravure printed products. SC paper is uncoated wood-containing paper, which has a smooth surface. The paper is made mainly from mechanical pulp with good bulk, but long-fibre chemical kraft pulp is also added for strength. SC paper can also be made from recycled fibre, to which virgin fibre is also added for strength. The paper is supercalendered with a high line load to achieve a smooth surface. Stone-ground wood is a mechanical pulp made from softwood blocks that are pressed against a wet rotating stone that has small grits that warm up the lignin, thereby separating the fibres from each other. In the kraft process, wood chips and chemicals are combined in digesters where heat and chemicals break down the lignin to separate the cellulose fibres from each other without seriously degrading them.

8.1 Case definition

This case study covers a cradle-to-grave carbon footprint calculation for a gravure printed leaflet, i.e. an advertisement in the form of a leaflet that is distributed to consumers by mail. The case study is assumed to take place in Finland, but alternative European scenarios were also conducted. The case study was carried out according to the life cycle assessment ISO 14040:2006 standard series and carbon footprint guidance document PAS 2050:2008, using both when applicable. The goals of this case study were:

- to identify the order of magnitude of the carbon footprint of a gravure printed leaflet as such general level information is not yet widely available.
- to estimate the variance in carbon footprint results caused by different selections made in the value chain of the product. A European perspective was selected in this scenario analysis.

The basic parameters of this case study were defined together with paper and printing industry representatives. Hence, this case study is not based on data concerning any specific gravure printed leaflet value chain. Rather, it represents a viable value chain. Basic information and assumptions related to the reference gravure printed advertisement case study are presented in Table 24.

Table 24. Assumptions for the reference case for a gravure printed advertisement.

Print product	Advertisement (unaddressed leaflet)
Printing	Gravure 4-colour printing
Paper	52 gsm SC paper 49% SGW[1], 22% SW kraft pulp[2], 29% fillers
Weight	20 g/piece, dryness 96%
Size	4 pages of A4, folded (40 cm x 50 cm)
Geographical aspects	Paper production, printing, delivery and disposal in Finland
Distribution	Directly to home by mail
End-use of product	Recycling 83%, Landfill 14%, Incineration 3%

[1] SGW = soft ground wood (mechanical pulp)
[2] SW = softwood kraft pulp (chemical pulp)

The functional unit of this case study is 1000 kg of advertisements delivered to the consumer. The system boundary is presented in Figure 47.

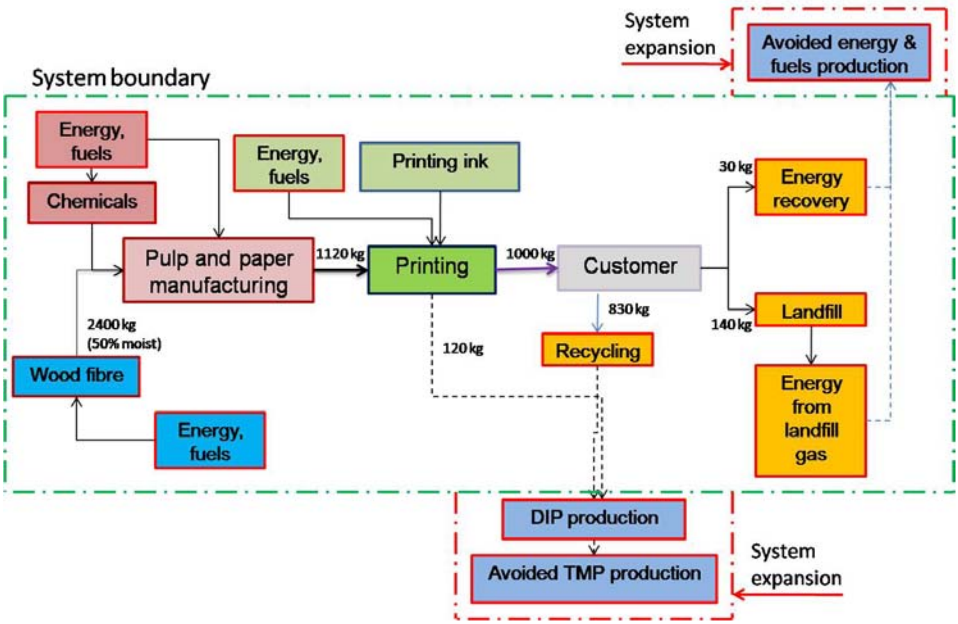

Figure 47. System boundary of the case study with fibre flow (moist).

The system boundary covers the whole life cycle from raw material production to the end-of-life treatment of the paper product, i.e. the life cycle from cradle to grave. The main steps of the life cycle are raw material acquisition, energy production, paper manufacturing, printing, product delivery to consumers and treatment of the waste paper after disposal. However, a significant amount of recyclable paper and excess power and heat are directed out of this product system. Two system expansions (see Figure 47) were applied in order to calculate the avoided emissions that are obtained with the use of recycled fibre and the use of excess energy produced in end-of-life treatment outside this product system. This is the approach that is suggested by the ISO 14040 life cycle assessment standards series. It was assumed that deinked pulp made from recycled paper replaces TMP production and that the electricity and heat obtained from waste incineration and landfill gas burning replace average Finnish electricity and heat production outside the studied system. This leads to a decrease in GHG emissions that can be credited to the studied product system.

The calculations are based on environmental data acquired from various databases and multiple companies. The data on gravure printing activities was acquired from both companies and the literature (Enroth & Johansson 2006, EIPPCB 2007). For more information, see Appendix F.

The paper mill was assumed to be integrated into a pulp mill. The majority of raw materials were assumed to be delivered from a closeby location, approximately 100–300 km with road transport. It was assumed that the final products would be delivered to consumers according to the typical direct mail delivery system: First, long-distance transport from the printing house to a local delivery centre with trucks, and then local delivery to consumers with lighter vehicles, e.g. vans, cars, mopeds and bicycles.

The copper and chromium coating applied on the printing cylinder was omitted in this study. Although the GHG emissions per unit of these metals are known to be rather high, the consumption of these metals was insignificant (less than 1 kg) per tonne of leaflets printed. The energy consumption of cylinder preparation was included in the printing house energy consumption data. Also, content creation (editorial work) for the advertisement was excluded from the study.

8.1.1 Studied scenarios

A scenario analysis was carried out in order to identify how different selections affect the carbon footprint of the product. The main focus was to determine the impacts if i) production of paper, ii) printing activities and/or iii) delivery and end-use take place in an average European Union country. In the reference case, all these activities were considered to take place in Finland. The uncertainty in the landfill emissions was evaluated as well. The studied scenarios are presented in detail in Table 25.

The location of the printing house or pulp and paper mill was studied in order to find out how high of an effect the emission factor of the power grid mix in the selected region has on the emissions from those activities. It is also interesting to determine the impact that the decision to produce paper from either recycled fibres or only primary fibres has on the carbon footprint of the whole value chain. It is also interesting to find out how big of an impact the different end-of-life structures in the European Union on average and in Finland have on the carbon footprint of the total value chain.

The base paper or printed product had to be transported between Finland and Central Europe in most of the studied scenarios. It was assumed that the paper was transported from/to Finland over a distance of 1000 km with a container ship and 500 km with a truck. The local delivery of the final product to customers was calculated both in Finland and in an average EU country with Finnish data. This data is not necessarily representative of the emissions of local delivery in Central Europe, where the population density is much higher. This adds uncertainty to the results. This approach was selected because there was insufficient data at hand on the Central European local delivery system.

Table 25. The studied scenarios: reference and five optional scenarios.

	Reference scenario	**Optional scenarios**				
	All Finnish	**Paper production in the EU**		**Printing in the EU**	**End-use in the EU**	**Low emissions from landfill**
	(PRIM FI FI FI)	(PRIM EU FI FI)	(DIP74 EU FI FI)	(PRIM FI EU EU)	(PRIM FI FI EU)	(PRIM FI FI FI low)
Selection of paper	Only primary fibres: 49% SGW, 22% SW kraft pulp, 29% filler Produced in Finland	Paper produced in average EU country from primary fibres	Paper produced in average EU country from recycled fibres: 74% DIP, 22% fillers, 4% TMP	*	*	*
Location of printing	Printed in Finland	*	*	Printed in average EU country	*	*
End-of-life scenarios	In Finland: Recycling 83% Landfill 14% Incineration 3%	*	*	In average EU: Recycling 63% Landfill 25% Incineration 12%	In average EU: Recycling 63% Landfill 25% Incineration 12%	*
Landfill emissions	High estimate	*	*	*	*	Low estimate

Note: Of the three digit codes (e.g. FI FI FI), the 1st stands for the location of the paper manufacturer, 2nd for printing and 3rd for end-use (* = same assumption as in the 'All Finnish' PRIM FI FI FI reference scenario).

8.2 Carbon footprint results

All greenhouse gas emissions were included in the carbon footprint calculation. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions have the biggest contribution to the carbon footprint. Chapter 2.2 presents more information about the principles of the carbon footprint calculation and the GWP conversion factors.

The result of carbon footprint calculation for the reference scenario is presented in Figure 48.

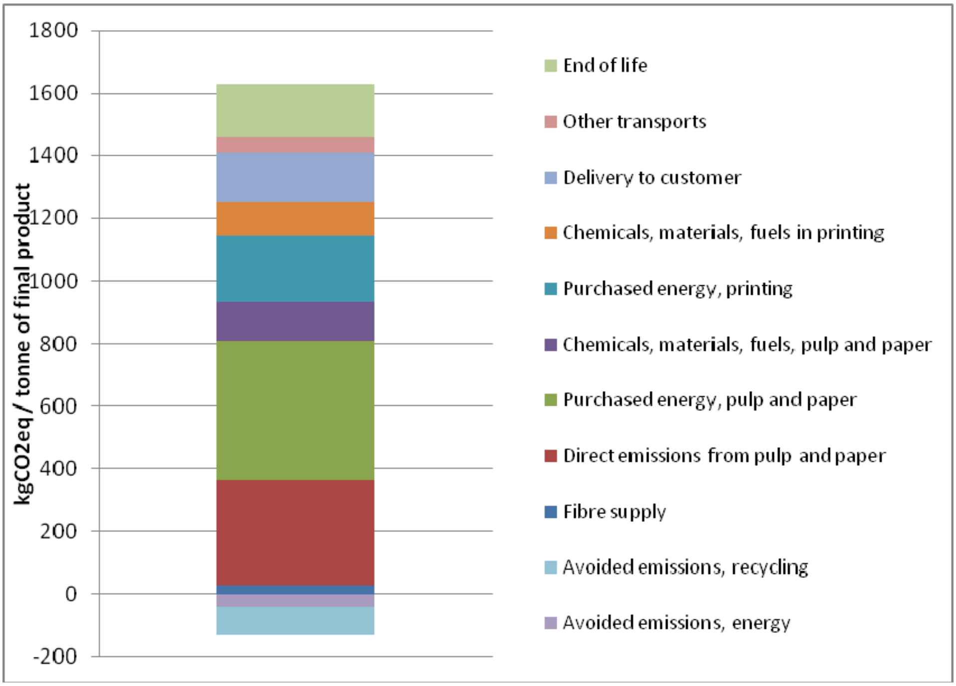

Figure 48. Carbon footprint results for the reference scenario for a gravure printed advertisement (PRIM FI FI FI). Note: The avoided emissions have not been subtracted from the total emissions and are shown as negative values.

The life cycle GHG emissions are around 1630 kg CO_2eq/tonne$_{product}$ for the studied gravure printed advertisement case. When the avoided emissions obtained from material and energy substitution are included, the carbon footprint can be considered to amount to 1500 kg CO_2eq/tonne$_{product}$. The shares of the GHG emissions accounted for by each life cycle phase are presented in Figure 49.

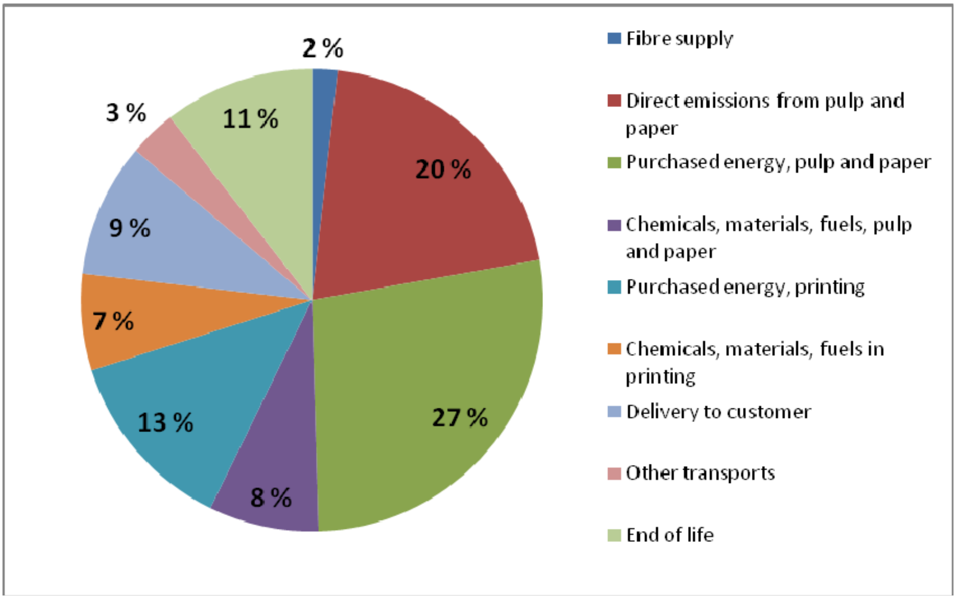

Figure 49. The share of GHG emissions accounted for by each life cycle phase in the reference scenario (PRIM FI FI FI) for a gravure printed advertisement.

Pulp and paper manufacturing contributes more than 50% (900 kg CO_2eq) of the life cycle GHG emissions, printing activities 20% (320 kg CO_2eq), and delivery to customer and end of life around 10% each (160 kg CO_2eq each). Detailed information is presented in Table 26 and in Appendix E.

However, this result is representative only for a gravure printed leaflet value chain that is similar to the assumptions made for this case (Table 24). Therefore, a scenario analysis is needed in order to define the range of life cycle GHG emissions for distinct value chains in Europe.

Table 26. The GHG emissions of the reference scenario for a gravure printed advertisement (PRIM FI FI FI) divided into each life cycle phase. The results are presented as absolute CO_2eq emissions [kg, g] and as a share of the life cycle [%]. Total emissions are presented for cradle-to-gate, cradle-to-grave and cradle-to-grave with avoided emissions.

	Life cycle emissions		**Share of total emissions**	
	kg CO_2e/ tonne	**g CO_2e/ piece**	**Cradle-to-grave [%]**	**Cradle-to-gate [%]**
Fibre supply	29	1	1.8%	2.3%
Direct emissions from pulp and paper	333	7	20.4%	26.6%
Purchased energy, pulp and paper	446	9	27.4%	35.6%
Chemicals, materials, fuels in pulp and paper	125	3	7.7%	10.0%
Purchased energy, printing	210	4	12.9%	16.7%
Chemicals, materials, fuels in printing	110	2	6.7%	8.8%
Cradle-to-gate GHG emissions	1253	26	76.8%	100%
Delivery to customer	153	3	9.4%	
Other transport	54	1	3.3%	
End of life	171	3	10.5%	
Cradle-to-grave total emissions (w/o avoided emissions)	1631	33	100%	
Avoided emissions, recycling	-90	-2		
Avoided emissions, energy	-42	-1		
Entire system (with avoided emissions)	1500	30		

8.2.1 Scenario analysis

Scenario analysis was carried out in order to quantify the impact of some variations in the value chain on the life cycle GHG emissions. The studied scenarios are defined in Table 25. In the following figures, the reference scenario is presented on the left if not otherwise stated. A figure summarizing all the scenarios is presented at the end of this chapter.

Because the pulp and paper manufacturing phase has a significant role in the life cycle GHG emissions of the product, different options for paper were studied. Three scenarios for SC paper were defined: the reference case with paper production from primary fibres with Finnish electricity mix, paper production from primary fibres with an average EU electricity mix and paper production with 74% deinked pulp (DIP) with best available technology (BAT) level in an average EU country (Figure 50). In the reference case, a five-year Finnish average energy production mix was applied for the production of purchased electricity and heat. (For more information about the energy production mixes, see Appendix B.)

DIP was studied only for the EU, because it is not a realistic scenario in Finland. Most of the paper (over 90%) produced in Finland is exported, and domestic paper consumption does not produce enough recycled fibre (DIP) for the production of 100% DIP paper, even though the overall paper recycling rate in Finland is very high (above 70%). In addition, Finland is a sparsely populated country, which poses challenges to organizing environmentally and economically feasible transportation of recycled fibre. Currently, the recycled fibre collected in Finland is used for the production of newsprint, catalogue paper, packaging and insulation materials, for example.

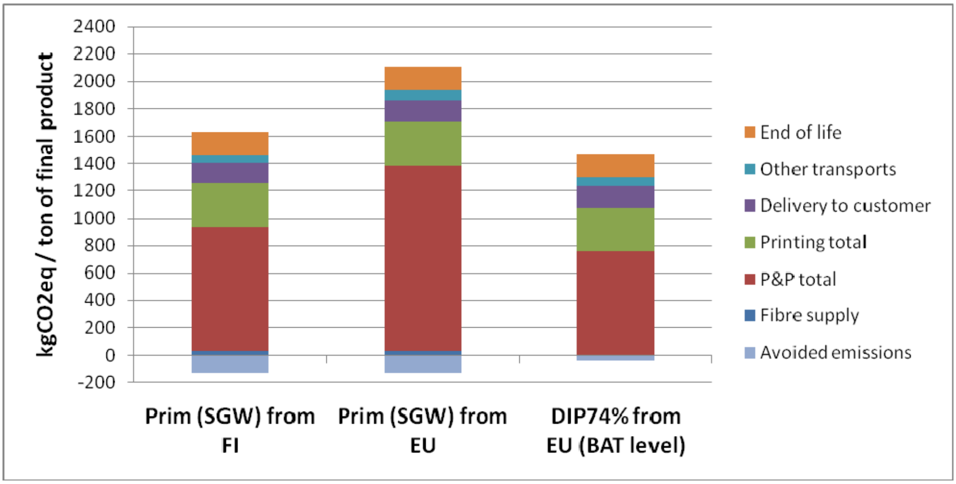

Figure 50. The impact of selection of SC paper on the life cycle GHG emissions: SC paper production from primary fibres in Finland (left), from primary fibres in EU and from deinked pulp (recycled paper) (74%) in EU with BAT level. Note: The avoided emissions have not been subtracted from the total emissions.

The difference between SC paper production in Finland and in an average EU country, roughly 350 kg $CO_2eq/tonne_{product}$, can be explained by the difference in the emission factors of the Finnish and average EU power grid mix, 250 kg CO_2eq/MWh and 500 kg CO_2eq/MWh respectively. The difference is mainly due to varying shares of fossil energy sources in the energy production profiles and due to the high share of efficient combined heat and power production (CHP) in Finland (IEA 2008, see also Appendix C). The technology level for the two cases is the same, i.e. conventional pulp and paper mills. The carbon footprint for the

DIP 74% scenario is about 150 kg CO_2eq/tonne$_{product}$ lower than for the reference scenario, although paper production in the DIP 74% scenario uses the average EU power mix. The technology for the DIP 74% scenario is on a BAT level, which reaches higher energy efficiency than the conventional technology level in all other scenarios. Some of the emission savings compared to the reference case can be explained by the difference in the technology level of the data.

It is interesting to compare how big of an impact the location of the printing activities has on the final results, as it is known that the GHG emission factor of the power supply has a focal role in carbon footprint calculations and the emission factor varies between different regions. Hence, the differences in the carbon footprint if the printing house was located in Finland or in an average EU country were studied (Figure 51). Note that the end use is assumed to happen in an average EU country; therefore, in Figure 51, the bar on the left does not represent the reference scenario.

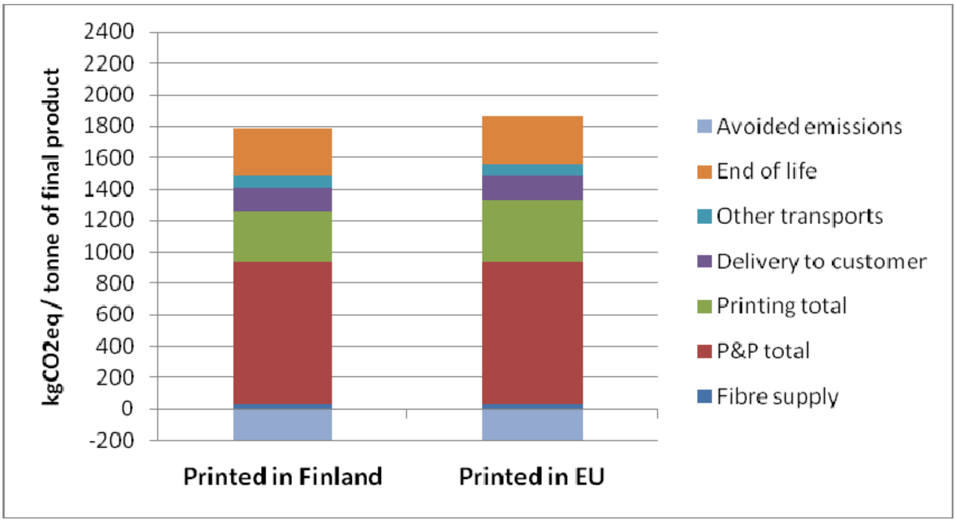

Figure 51. The impact of the location of printers: Comparison of GHG emissions when the leaflet is printed in Finland (FI FI EU) or in an average EU country (FI EU EU). In both scenarios, end use is the average figure for EU countries. Note: the avoided emissions have not been subtracted from the total emissions.

The impact of increased emissions from the power supply for the printing house is limited, 80 kg CO_2eq/tonne$_{product}$, for the whole value chain.

The structure of waste management differs significantly between Finland and the EU on average. The shares for recycling, incineration and landfilling in

Finland are 83%, 3% and 14%, respectively (Paperinkeräys Oy 2010, Eurostat 2010). In the EU, on average, the shares are 63%, 12%, 25% (ERPC 2008, Eurostat 2010). A comparison was made between the two waste management structures (Figure 52).

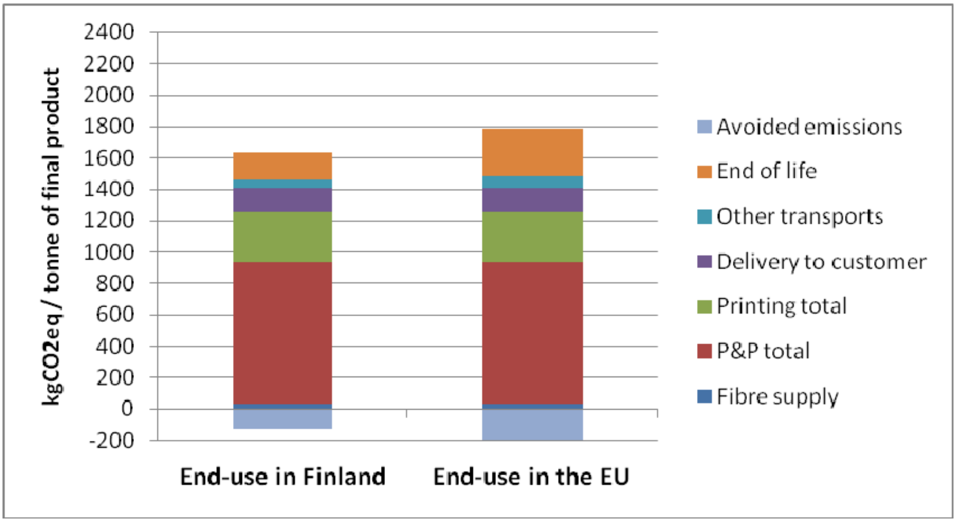

Figure 52. The impact of end-of-life scenarios: Comparison of the GHG emissions of waste management in Finland (FI FI FI) and in the whole EU on average (FI FI EU). Note: the avoided emissions have not been subtracted from the total emissions.

As a smaller share of paper is landfilled in Finland than in the EU on average, the emissions from end of life are approximately 130 kg $CO_2eq/tonne_{product}$ smaller. However, the higher share of energy end use in the EU, on average, leads to GHG emission compensation, i.e. avoided emissions of approximately 100 kg $CO_2eq/tonne_{product}$. Hence, these two distinct end-of-life structures result in no significant differences in the life cycle carbon footprint results.

When the end-of-life emissions are considered, it has to be remembered that there is significant uncertainty in the emission data on paper landfilling (see Chapter 4.1.4 for more details). The result for high and low estimates for GHG emissions is presented in Figure 53.

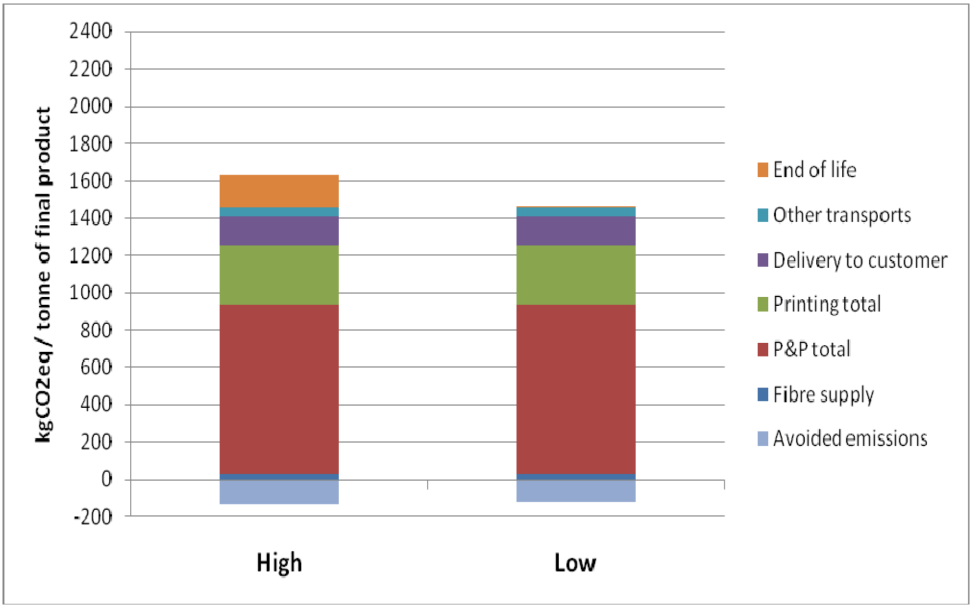

Figure 53. The impact of landfill emissions: Comparison of life cycle GHG emissions with high and low estimates for landfill GHG emissions (Cases PRIM FI FI FI high and low). Note: the avoided emissions have not been subtracted from the total emissions.

The uncertainty caused by landfill GHG emission data is on the order of 150 kg $CO_2eq/tonne_{product}$ for an unaddressed advertisement leaflet disposed of in Finland. The results of all the scenarios are presented in Figure 54 and Figure 55.

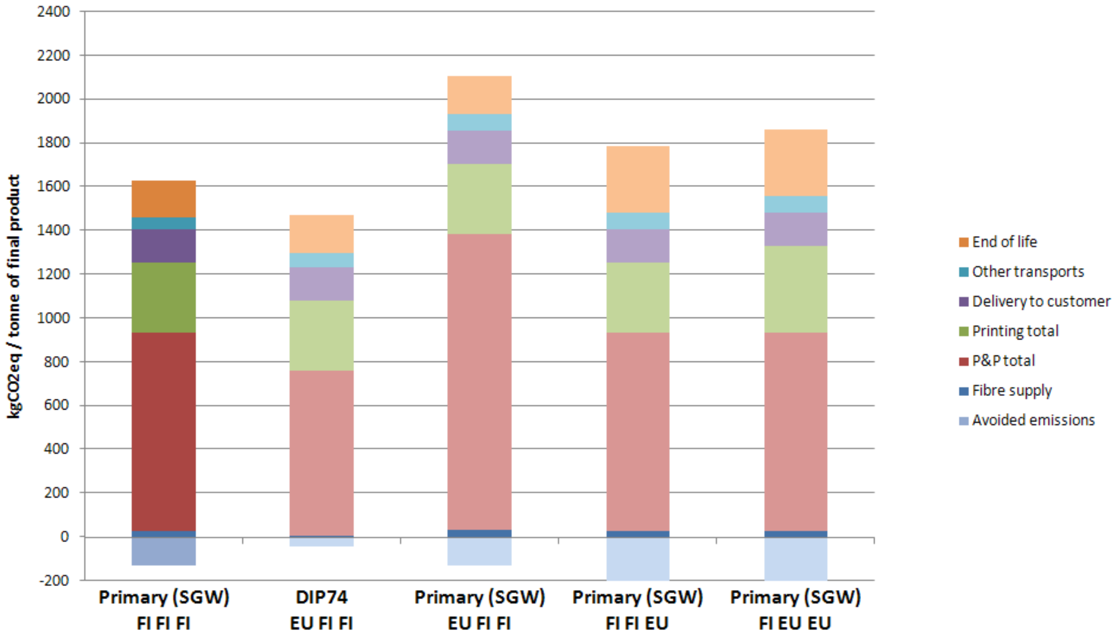

Figure 54. Life cycle GHG emissions of the reference scenario and four optional scenarios[14]. Note: the avoided emissions have not been subtracted from the total emissions.

[14] The three two digit codes (e.g. EU FI FI) stand for the location of the different activities of the value chain. The 1st represents the location of paper production, the 2nd the location of the printing house and the 3rd the location of delivery to consumer and corresponding structure of waste management. For example, FI FI FI is the all Finnish reference scenario.

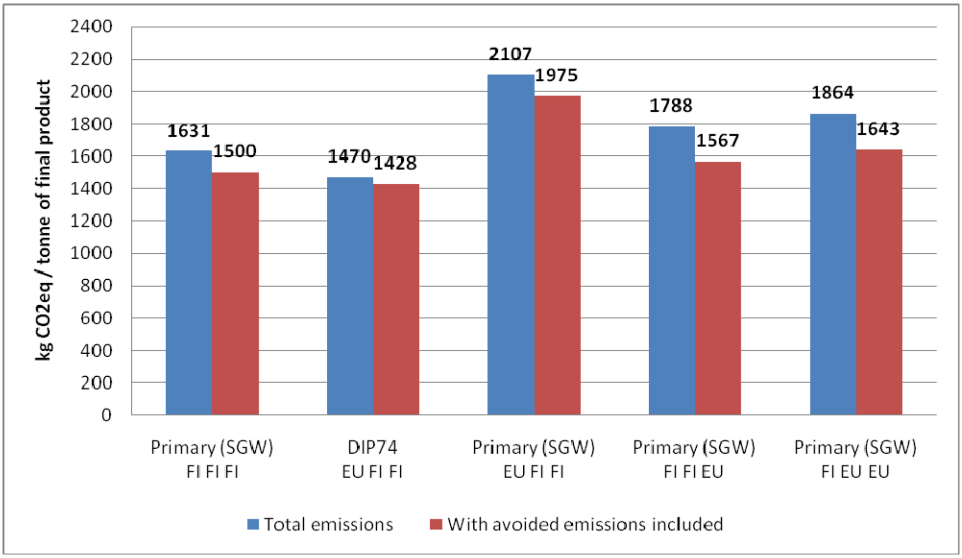

Figure 55. Comparison of life cycle GHG emissions of the reference scenario and four optional scenarios with and without avoided emissions. Results are presented with total emissions (blue on the left) and with avoided emissions subtracted from the total emissions (red on the right).

We can see from Figure 54 that the carbon footprint of the gravure printed advertisement varies significantly between different value chains. It is important to note that the avoided emissions tend to level out the differences between the studied scenarios (Figure 55). It should also be noted that the technology level in the DIP 74 EU FI FI case is at a BAT level (high energy-efficiency) and in the other cases at a conventional level. This might explain part of the differences in the results. Data from different technology levels was used due to lack of comparable data. In this study, the total GHG emissions for the reference case are 1630 kg CO_2eq/tonne$_{product}$ while the variance is from 1470 to 2110 kg CO_2eq/tonne$_{product}$ for the optional scenarios. The results are presented with and without avoided emissions in Table 27 and Table 28.

Table 27. Life cycle GHG emissions of the reference scenario and four optional scenarios per tonne of product. Results are presented with and without avoided emissions.

	Reference				
	Primary FI FI FI	DIP 74% EU FI EU	Primary EU FI FI	Primary FI FI EU	Primary FI EU EU
	kg CO_2eq	kg CO_2eq	kg CO_2eq	kg CO_2eq	kg CO_2eq
Total	1631	1470	2107	1788	1864
With avoided	1500	1428	1975	1567	1643

Table 28. Life cycle GHG emissions of the reference scenario and four optional scenarios per product (20 g, 4 pages of A4, folded). Results are presented with and without avoided emissions.

	Reference				
	Primary FI FI FI	DIP 74% EU FI EU	Primary EU FI FI	Primary FI FI EU	Primary FI EU EU
	g CO_2eq	g CO_2eq	g CO_2eq	g CO_2eq	g CO_2eq
Total	33	29	42	36	37
With avoided	30	29	40	31	33

It can be seen from the results that the GHG emission factor of the electricity mix in the region of the studied activity plays a key role in the carbon footprint calculations. Therefore it is best to locate the energy intensive paper production from virgin fibres to a region with low GHG emissions from purchased energy. A certain amount of primary fibre is always needed as an input to produce the recycled fibres since the fibres can only be recycled for a certain number of times. However, caution should be taken in drawing conclusions from this result, as the data for DIP 74% scenario was on different technological level (best available technology) than the data in all the other scenarios (conventional technology). It was impossible to identify if the reason for lower GHG emissions was caused only by the difference in the technology level or if the use of recycled fibre really leads to a reduction in life cycle GHG emissions.

The location of printing house has a low impact on the life cycle GHG emissions of the gravure printed advertisement. The reason for this is the relatively small purchased power need compared to the pulp and paper production phase. The two distinct end-of-life structures studied (Finland and average EU) result in no significant differences in the life cycle carbon footprint results.

8.3 Conclusions and discussion

The aim of this case study was to identify the order of magnitude of the carbon footprint of a gravure printed leaflet. The second goal was to estimate the variance in carbon footprint results caused by different selections made in the value chain of the product, especially in Europe. The result for the reference case was on the order of magnitude of 1500–1700 kg $CO_2eq/tonne_{product}$, while the variance for all the studied scenarios was 1400–2100 kg $CO_2eq/tonne_{product}$.

A typical print run of a gravure printed advertisement that is delivered nationwide ranges from one million to a few million copies. A million copies equal 20 tonnes of print products in this case study. The GHG emissions for this print run amount to approximately 30–40 t CO_2eq. This is equivalent to the yearly GHG emissions from the electricity use of 6–8 typical Finnish houses with electrical heating or 50 Finnish flats with district heating[15]. On the other hand, the GHG emissions per one 20 g (four 40 x 50 cm pages) gravure printed advertisement are 30–40 g CO_2eq. This equals the GHG emissions that are caused by the electricity consumed in watching a modern TV for 50 minutes in Finland[16]. It should be noted that manufacturing, the electronic transmission of programmes and TV disposal are excluded from the numbers. 30–40 g of CO_2 equivalents are created also by driving a car for less than 0.3 kilometres.[17]

[15] An average 120 m^2 Finnish house for four persons (with electrical heating) consumes 18 MWh of electricity per year. An average 75 m^2 Finnish flat for three persons in an apartment building (with district heating) consumes 2.6 MWh of electricity per year. (Adato Energia 2008, Fortum 2010). The emission factor for Finnish electricity from grid is 250 kg CO_2eq/MWh.

[16] A modern 32–37'' LCD TV set consumes 0.15 kWh_e/h (Helsingin Energia 2010). This is the predominant technology in Finnish homes now and in the near future (Adato Energia 2008). The emission factor for Finnish electricity from grid is 250 kg CO_2eq/MWh.

[17] A new passenger car emits on average 164 g CO_2eq/km (lipasto.vtt.fi).

Production of printing paper was found to be the most significant life cycle phase in terms of GHG emissions, with a 50–75% share of the total emissions. It is not surprising that paper manufacturing accounts for a large share, since paper is the main component of the product (over 99% of the weight of the final product). The power generation mix in the country where the paper is printed proved to be a key factor, along with the use of deinked pulp. Caution should be taken in drawing conclusions from the results on deinked and virgin fibre pulp. It was impossible to identify if the reason for lower GHG emissions in the DIP 74% scenario was caused only by the difference in the technology level in the data (BAT versus conventional) or if the use of recycled fibre really leads to a reduction in the life cycle GHG emissions.

Printing is the second important phase, responsible for 15–20% of the emissions. The delivery of the printed product to the consumer also accounts for a high share of the life cycle GHG emissions, about 10%. This can be explained by the fact that the ultimate delivery to homes is handled with multiple vehicles on a widespread area. Since one vehicle only carries tens of kilograms of product, the emissions caused by the delivery per product are much higher than, for example, in long-distance delivery with trucks that carry many tonnes of products.

From the perspective of printing houses, there are a few key points to concentrate on in terms of controlling GHG emissions. The paper used for printing has the most significant impact on the gravure printed product's carbon footprint. In actual printing activities, the production of the energy consumed in the process is responsible for 60–70% of the GHG emissions from the printing phase. Thus it is more important to focus on energy efficiency than the selection of chemicals or inks. It should be noted, however, that there is limited environmental data available on the production of chemicals and printing inks and additional research on this area is needed. Furthermore, it cannot be overlooked that the delivery of the product to homes and offices causes significant GHG emissions, approximately half of the GHG emissions released in the printing phase.

Energy production is a central source of GHG emissions in our society; therefore it is emphasized in carbon footprint studies. However, it should be kept clearly in mind that the carbon footprint is only one indicator of the environmental performance of a product. All the other environmental aspects can only be covered with full life cycle assessment.

9. Carbon footprint of a sheetfed offset printed book

Chapter 9 presents the results of a carbon footprint case study for a hardcover book (a novel) printed by sheetfed offset. The life cycle of the product was covered from the cradle to the retailer's warehouse. In addition, the carbon stored in the product was calculated according to PAS 2050 guidelines. It is assumed that the product is manufactured and retailed in Finland.

In 2009, sales of printed books in Finland amounted to over 250 million euros. Of the total value, over 44 million euros represented sales of fiction (Finnish Book Publishers Association 2010). In 2008, 77% of Finns bought at least one book. Altogether, private persons bought 22 million books (Suomi lukee 2008). The total circulation of books was 26 million in 2008 and the share of fiction books was one fifth (VKL 2009). The amount of time Finnish readers dedicated to reading books in 2007 was around 25 minutes per day (http://www.sanoma lehdet.fi/).

Book manufacturing is a multistage process and several different bookbinding techniques are used. The size, weight, design and intended use of the product determine whether the book will be hard or soft cover, how it will be bound and what kinds of materials and techniques are used in the bookbinding process. In Finland, new novels are typically published as hardcover books while reprints are often published as paperbacks.

Sheetfed offset printing is used for the production of high-quality books. It is a process that employs presses with sheet sizes of SRA3 to 2 x 2.5 metres. There are many sheetfed printing houses and each house normally has several printing presses. Typical print runs are between 300 and 25 000 copies. Variation between different products can be high.

Offset lithography is a complex printing process in which the printing plate is divided into chemically differing image and non-image areas, where the difference is induced by photochemical reaction. In the printing process, the plate is first dampened with fountain solution, which adheres to the non-image areas of the plate. In the following stage, nip ink rollers apply ink only to the image areas of the printing plate. The image on the plate is transferred via a rubber blanket to the substrate under nip pressure. The print quality of sheetfed printing is extremely high, but it can be lowered for economical reasons.

Inks used in sheetfed offset are normally mineral or vegetable oil-based and they dry by polymerization. IR dryers are used to speed up the polymerization process. UV-curing inks are claiming a growing share of sheetfed offset printing. The aluminium-based printing plates are recycled.

Several paper grades, cover materials and special effects can be used in book printing. When considering hardcover books, the cover of the book is typically made from coated fine paper and grey board. Also the jacket of the book is made from coated fine paper, which is very high-quality printing paper made from bleached chemical pulp. The term woodfree paper is also used. In chemical pulping, wood chips and chemicals are combined in digesters where heat and the chemicals break down the lignin to separate the cellulose fibres from each other without seriously degrading them. The kraft process is the dominant chemical pulping method.

Coating the paper gives it a smooth and even surface and enables very high print quality. The clay and calcium carbonate ($CaCO_3$) coating is usually made with two layers and the top coating is done as blade coating. The pigment content of coated fine paper can be higher than the fibre content when weight is considered. The board for the book cover is grey board, which is made from recycled fibre. The recycled paper is not bleached during the board-making process. The board has a strong stock sizing, making the board very tough and yet flexible.

The inner sheets and endpaper are made from uncoated fine paper, which is high-quality printing paper made from bleached chemical pulp. The term uncoated woodfree paper is also used. The surface of the uncoated paper is usually sized to gain good surface strength and water resistance. Pigments are used in the base paper to achieve better whiteness and opacity. The paper is machine calendered to obtain the preferred surface properties.

9.1 Case definition

The goal of the case study was to examine the carbon footprint of a hardcover book. The scope of the study was cradle to retailer, in which end of life was excluded from examination. The life cycle includes the harvesting processes, manufacturing of chemicals and other raw materials for pulp and paper manufacturing and printing, and all the processes included in paper making and printing and related transport.

The case definition was conducted together with paper and printing industry representatives. The case product is an example of a hardcover novel that could be manufactured and sold in Finland. The functional unit used in the study was one book.

As in the photobook case, the decision to limit the study to the cradle-to-retailer approach only was made because there was no data available concerning the end of life of books. Some assumptions could have been made, but since there is remarkable uncertainty associated with the recycling rates of books and the decomposition of books in landfills, the uncertainty of end-of-life calculations would have grown significantly. Consequently, it was more reasonable to calculate the cradle-to-customer results and then discuss the impacts of end-of-life decisions. Furthermore, the climate impacts related to writing the book and editorial work were excluded from the study.

Like photobooks, it can be argued that books are often stored at home for a long time and consumers rarely face the decision of whether to dispose of used books. In addition, transportation from retailer to consumer was excluded due to high variability and differences in transportation methods – for example, the consumer can walk to the bookstore, causing zero emissions, or drive there by car only to buy one book, causing maximum emissions.

The case definition is presented in the following table (Table 29).

Table 29. Case assumptions for a hardcover book.

Print product	Sheetfed offset printed book, hardcover, sewn Components: Cover, inner sheets, end papers, jacket Format: 205 mm x 135 mm 300 pages
Printing	Sheetfed offset (SFO)
Paper	Cover: 1300 gsm board (100% defibered pulp from board and unbleached paper) + 150 gsm coated fine paper (11% pine kraft pulp, 34% birch kraft pulp, 50% pigments, 5% binders) Inner sheets: 90 gsm uncoated fine paper (21% pine kraft pulp, 50% birch kraft pulp, 25% fillers,4% binders) End papers: 150 gsm uncoated fine paper (21% pine kraft pulp, 50% birch kraft pulp, 25% fillers,4% binders) Jacket: 150 gsm coated fine paper, water varnish
Weight and dryness	500 g / book, dryness 96%
Geographical aspects	Paper production, printing and delivery in Finland
Distribution	Transportation to retailers included, transportation to customer excluded
Storage at home	50 and 100 years

Data on paper manufacturing was derived from the KCL Ecodata database. Data on printing was collected from four Finnish book printers. The used maculature percentage for book manufacturing was 28%. Data on printing ink was derived from the Ecoinvent database, representing average data on offset printing ink. The offset printing ink used in the study includes both mineral and vegetable oils.

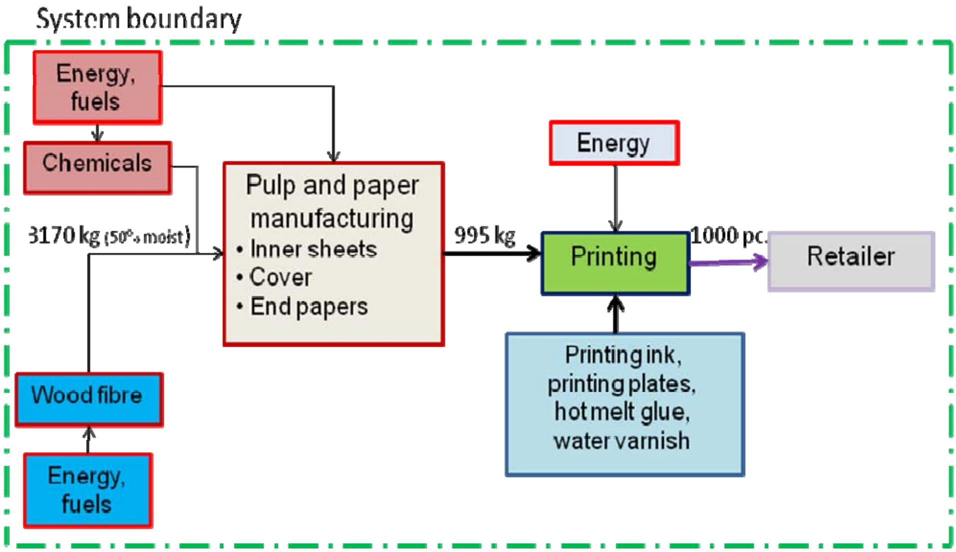

Figure 56. System boundary of the studied book case with fibre flow (moist).

When the studied system was examined, the impacts of each component of the book as well as printing were studied separately. The system boundary is presented in Figure 56. The studied components were the inner sheets, cover and end papers. Some minor raw materials used in the bookbinding process at the printing house were excluded from the study due to their minor impact (e.g. bookbinding thread, mull, etc.) In addition, direct emissions from printing, the purchased electricity of printing houses, and chemicals and materials used in printing were studied separately. The impact of transportation was also studied separately. A more detailed description can be found in Table 30.

Table 30. Life cycle of a sheetfed offset printed book is divided between the different components of a book.

Life cycle stage	More detailed	Included processes / notes
Inner sheets	Woodfree, uncoated, 90 gsm, manufactured in Finland	Fibre supply, pulp and paper manufacturing, chemical and other raw material manufacturing, fuels and energy, wood, chemical and fuel transportation.
Cover	Cover sheet: Woodfree, coated, 150 gsm, 50% pigments, manufactured in Finland Board for cover: recycled board, 1300 gsm, manufactured in Europe Jacket: Woodfree, coated 150 gsm, printed and varnished with water varnish	Papers and board: Fibre supply, pulp and paper manufacturing, chemical and other raw material manufacturing, fuels and energy, wood, chemical and fuel transportation. Note! Jacket printing takes place in the printing house and thus emissions from printing are allocated to printing, not to the cover. Varnishing with water varnish (incl. varnish manufacturing) is included in chemicals, materials and fuels used in printing, not allocated to the cover.
End papers	Woodfree, uncoated, 150 gsm, manufactured in Finland	Fibre supply, pulp and paper manufacturing, chemical and other raw material manufacturing, fuels and energy, wood, chemical and fuel transportation,
Direct emissions from printing	Direct emissions from printing, e.g. from fossil fuel combustion	There are no direct GHG emissions from the SFO printing site, but it is shown in the figures to guarantee the transparency of reporting.
Purchased energy in printing	Emissions associated with purchased electricity in printing	Production of grid electricity.
Chemicals, materials and fuels in printing	Printing ink, printing plates, water varnish, hot melt glue	Manufacturing of printing ink, printing plates and glues needed to produce a book. Varnish: water varnish manufacturing. Hot melt glue: manufacturing of hot melt. Note! Includes also the energy use of varnishing and gluing.
Transportation	Transportation in the studied system	Paper, printing ink and printing plate transportation. Transportation of books from printing house to retailers. Assumed transportation distances and modes: 150 km Truck 9 t and 50 km Truck 3 t. Note! Does not include wood or other raw material transportation in paper production. Such transportation is included in paper manufacturing (see above).

9.2 Carbon footprint results

The cradle-to-retailer carbon footprint of a hardcover book is 1160 g CO_2eq, equalling 1.2 kg CO_2eq/book (Figure 57). The assumed weight of one book was 500 g and the number of pages 300. The carbon footprint of the product naturally varies depending on the size of the product and the number of pages. For an edition of 5000 books, the carbon footprint would be approximately 5800 kg CO_2 equivalents and for 2000 books (1 ton of books) approximately 2300 kg CO_2eq.

End of life was excluded from the study, but if it would have been included, the greenhouse gas emissions would have probably increased. This is due to the decomposition of paper in landfills (if all books are not recycled properly or combusted). On the other hand, fibres could be recycled and virgin fibre production could be prevented.

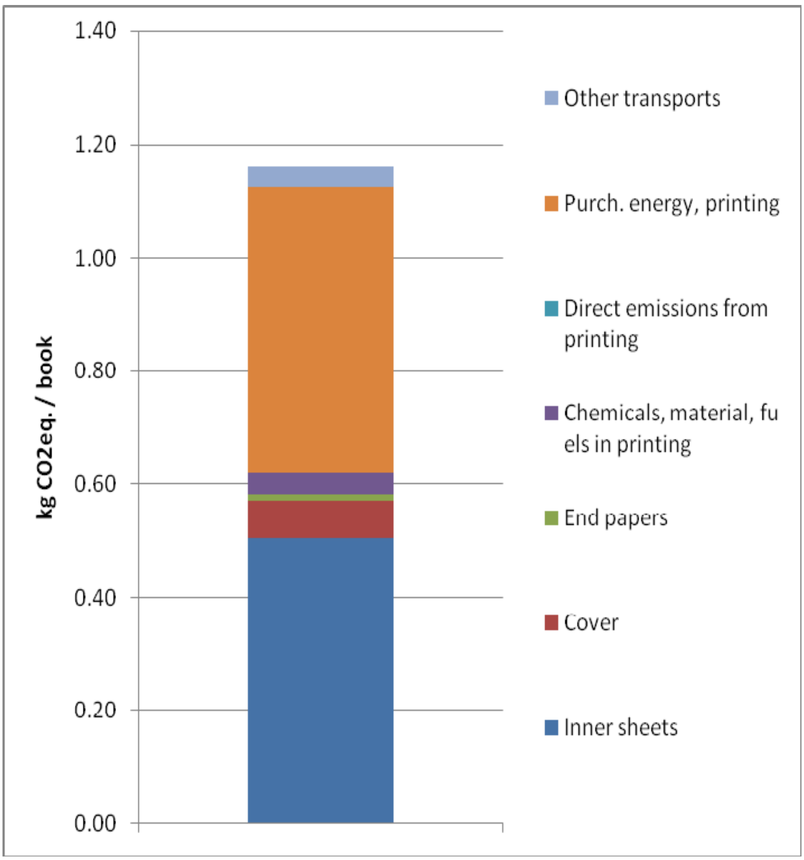

Figure 57. Carbon footprint of a hardcover book [kg CO_2eq/book].

Figure 58 shows the relative shares of each component in the carbon footprint of a book. Manufacturing of papers used in the book (inner sheets, cover and end papers) accounts for a total share of 51% and the printing phase for about 46% (production of purchased energy for printing and manufacturing of chemicals, materials and fuels) of the total cradle-to-customer greenhouse gas emissions.

The share of GHG emissions related to the printing phase seems to be relatively high when compared to other case products presented in this report. This can be explained by the complexity of the bookbinding process. The sheetfed offset process is quite slow and the bookbinding process (for hardcover books) has several stages. Compared to coldset offset and heatset offset machines, sheetfed offset machines are much smaller in size and the bookbinding process adds many additional phases to the printing phase. This increases the energy consumption in the printing house (see also Table 4 in Chapter 3.1.1).

It has to be noted that other transport does not include the transportation of wood and chemicals to paper mills – such transportation is included in paper manufacturing.

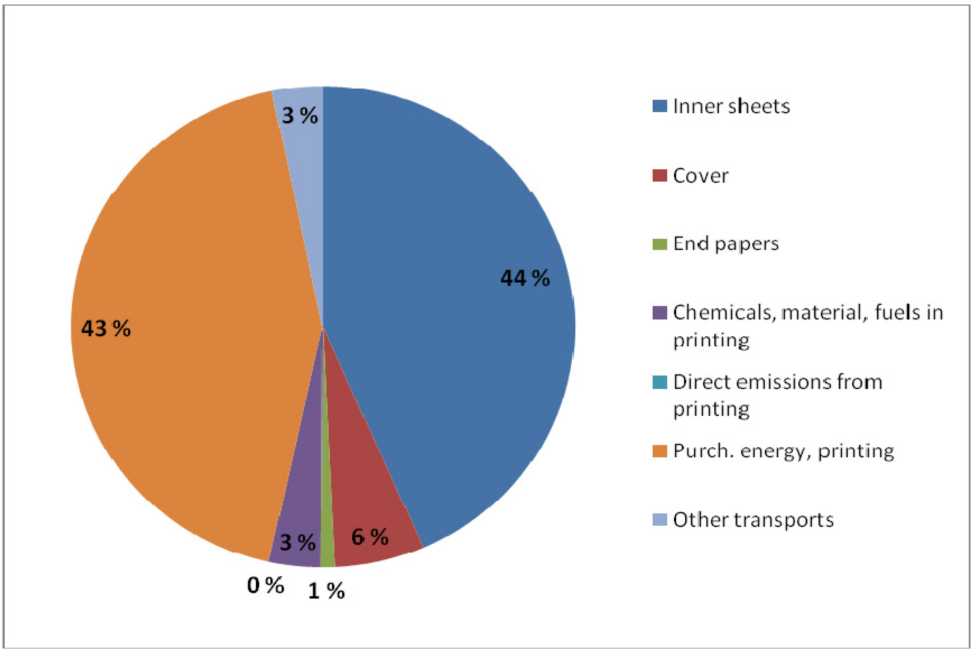

Figure 58. Relative shares of each component of a book in the carbon footprint.

9.3 Calculating carbon storage according to PAS 2050

As mentioned in Chapter 2.2.1, PAS 2050 allows the impact of carbon storage to be credited from the carbon footprint of a product if "*more than 50% of the mass of carbon (of biogenic origin) in the product remains removed from the atmosphere for one year or more following the production of the product*". In this study, it was assumed that a book is kept for 5, 50 and 100 years in a bookshelf and the carbon storage is calculated for that time. The calculation of carbon content and carbon storage is presented in Appendix H. The results are shown in Table 31.

Table 31. Carbon storage and carbon footprint of a hardcover book calculated according to the PAS 2050 calculation framework for assumed storage times of 100 years, 50 years and 5 years. The weight of the book is 500 g (including 300 pages) in 205 x 135 mm format. The carbon content of the product is expressed as carbon dioxide (CO_2). For assumptions related to carbon content of product, see appendix H.

	Weight of the book	**Unit**	**500 g**
	Cradle-to-gate carbon footprint	CO_2eq.	1160 g
	Carbon content of a book	C content as CO_2	880 g
Storage of 100 years, then 100% degradation	Carbon storage that can be credited from carbon footprint	CO_2	880 g
	Carbon footprint according to PAS 2050	CO_2eq.	280 g
Storage of 50 years, then 100% degradation	Carbon storage that can be credited from carbon footprint	CO_2	440 g
	Carbon footprint according to PAS 2050	CO_2eq.	720 g
Storage for 5 years, then degradation of 20%/year	Carbon storage that can be credited from carbon footprint	CO_2.	60 g
	Carbon footprint according to PAS 2050	CO_2eq.	1100 g

Carbon storage in this example is calculated for one book. Two different assumptions are made concerning the degradation rate of carbon in the book:

- Book is stored for 50 or 100 years, after which it is destroyed (e.g. combusted) immediately and the carbon is released back to the atmosphere.
- Book is stored for 5 years, after which the carbon degrades at a rate of 20% per year.

However, usually the situation is not that straightforward and the carbon in the book might be released slowly to the atmosphere (e.g. when degrading in a landfill). If multiple books are studied, some of them are probably stored only for a while whereas some of them might be stored for a very long time. The examples in this report illustrate three possible storage scenarios and show that the carbon storage benefit is strongly dependent on the time frame studied.

According to PAS 2050 it could be concluded that the longer carbon is stored in a product, the smaller the carbon footprint of that product. However, it is important to decrease actual emissions and not to rely too much on the carbon storage benefits.

9.4 Conclusions and discussion

This chapter presented the carbon footprint results for a sheetfed offset printed hardcover book. The result was divided between the different life cycle stages according to the materials used in the product. The life cycle of the book was studied from the cradle to the retailer's warehouse, excluding the end use and editorial work. PAS 2050 guidelines were followed in the calculation.

Based on the case study, the cradle-to-retailer carbon footprint of one book is 1160 g CO_2eq. The book was assumed to weigh 500 g and include 300 pages in 205 x 135 mm format. For edition of 2000 books (1000 kg in terms of weight), the carbon footprint would be approximately 2300 kg CO_2eq. The transport to the retailer contributes less than 1% of the total GHG emissions, therefore the cradle-to-gate carbon footprint is virtually the same as cradle-to-retailer.

The manufacturing of papers and board used in the book accounts for a total share of 51% of the cradle-to-retailer carbon footprint. The printing phase contributes about 46% of the total cradle-to-retailer greenhouse gas emissions. The GHG emissions related to the printing phase are mainly due to the production of purchased energy for the printing house, since no direct GHG emissions occur from the printing house. The manufacturing of materials and chemicals for printing is in a minor role.

The high share of energy consumed in the printing house can be explained by the complexity of the book binding process, which includes several different stages. Compared to many other paper products, hardcover books are usually assumed to have long lifespans. Sewn books are particularly durable, lasting for several reading times and thus for many years.

It should also be noted that there may be great variety between different kinds of books, depending on, e.g. the binding and materials used. These variations likely have an impact on the carbon footprint of the book. In addition, the size of the carbon footprint is of course affected by the weight of the product and number of pages. Thus this case study provides one example of a carbon footprint for a sheetfed offset printed book. If compared with other studies, the used assumptions and system boundaries should be carefully considered.

The cradle-to-retailer carbon footprint per one book is about 1160 g CO_2eq. These emissions equal the GHG emissions that are caused by driving a car for about 7 km[18] or the electricity consumed in watching a modern TV for about 30 hours in Finland[19]. It should be noted that manufacturing, the electronic transmission of programmes and TV disposal are excluded from the numbers.

End of life was excluded from the study due to lack of data and the fact that the end-of-life assumptions and allocations that would have to been made in order to carry out a full life cycle assessment would have increased the uncertainty remarkably. However, on the basis of the other cases, it can be recommended that consumers should not dispose of their books to landfill after use but recycle or dispose of them to energy recovery. If a book is recycled with other household paper waste, its covers should be separated and recycled with board waste (if they are board) or disposed to energy recovery (if other materials) and the inner sheets with newspapers and magazines. In order to give more precise recommendations concerning end of life, more research is needed, especially concerning the recycling rates of books.

Additionally, the carbon stored in the book was calculated according to PAS 2050 guidelines. The assumed storage time was 5, 50 and 100 years. As a conclusion, it can be stated that for paper products, a rather long storage time needs to be expected before considerable benefit or credit is created. By following the principles of PAS 2050, the carbon credit for five-year storage of a book is 5% of the total carbon footprint. When the book is stored for 100 years, the total carbon content of the product can be credited from the carbon footprint, and the credit increases to 75% of the total carbon footprint. The publishing of the ISO 14067 standard for carbon footprint of products will probably determine how the biogenic carbon stored in the products will be handled and presented in carbon footprint calculations in the future (see Chapter 2.2.3). At the time of writing, the development of the standard was still ongoing.

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[18] A new passenger car emits on average 164 g CO_2eq./km (lipasto.vtt.fi).

[19] A modern 32–37'' LCD TV set consumes 0.15 kWh_e/h (Helsingin Energia 2010). This is the predominant technology in Finnish homes now and in the near future (Adato Energia 2008). The emission factor for Finnish electricity from grid is 250 kg CO_2eq/MWh.

10. Carbon footprint of print products and their role in Finnish consumption

In Chapter 10, the results of the ENVIMAT model (Seppälä et al. 2009) are analyzed from the viewpoint of production and consumption. The ENVIMAT model describes the life cycle impacts of the Finnish economy at the macroeconomic level. It includes the environmental impacts of 150 industries; individual sectors include, for example, the manufacturing of pulp and paper, the manufacturing of paper products, printing and publishing.

As the focus is on printed products, only the publishing and printing sectors are considered in this work. The aim of the study was to evaluate the climate impacts (carbon footprint) of Finnish print production. It should be noted that only domestic use is included in the figures and thus the share of production exported abroad is excluded from the results. In addition, the share of the total climate impacts of Finnish households accounted for by newspapers, books and other paper products were studied. (For a description of the ENVIMAT methodology, see Chapter 2.3.)

10.1 Climate impacts of printed products in 2005

Based on the ENVIMAT model, the carbon footprint of the final products of Publishing was 489 000 tonnes CO_2eq and that of Printing 181 000 tonnes CO_2eq in 2005 (classification of the Printing and Publishing sectors is presented in Chapter 2.3.1). The results are composed of all the final products the sectors produced in Finland, but not their intermediate products that, according to the principle of life cycle thinking, are linked to other product chains (see Chapter 2.3.2).

According to the contribution analysis, which exposes the sources of CO_2eq along the life cycle, electricity has the greatest contribution (about one third) to climate impacts in both of the sectors (see Figure 59 and Figure 60). Electricity comprises the direct electricity consumption of the sector and also the electricity consumption of the supplier sectors, such as the pulp and paper industry. All the sectors contributing less than 2% to the carbon footprint are compiled together in "Others", e.g. foodstuffs, clothing, maintenance services, banking services.

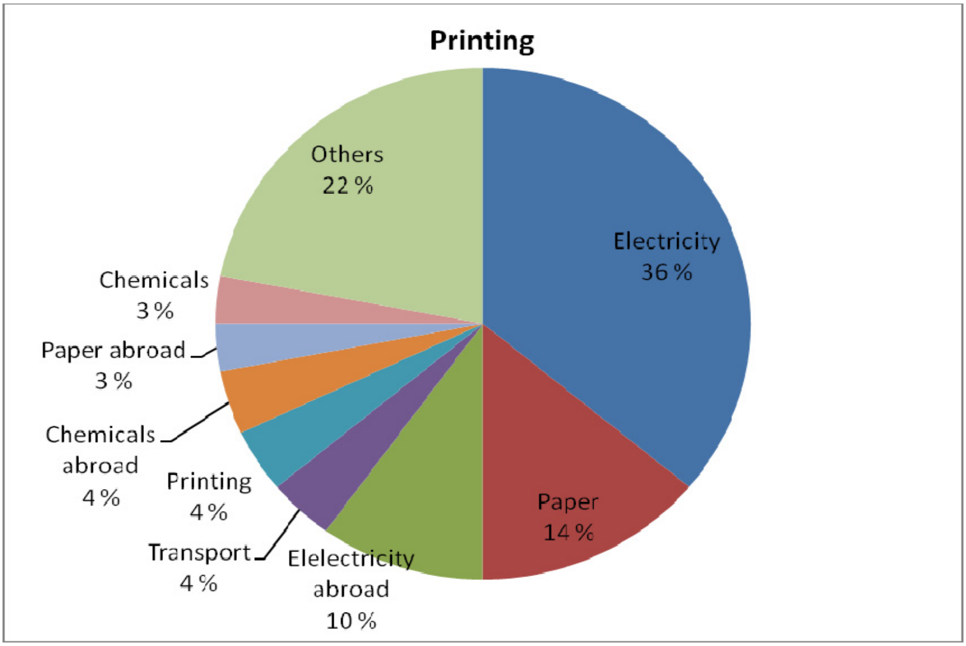

Figure 59. Sources of CO_2eq caused by the Finnish printing sector (final products) in the ENVIMAT model.

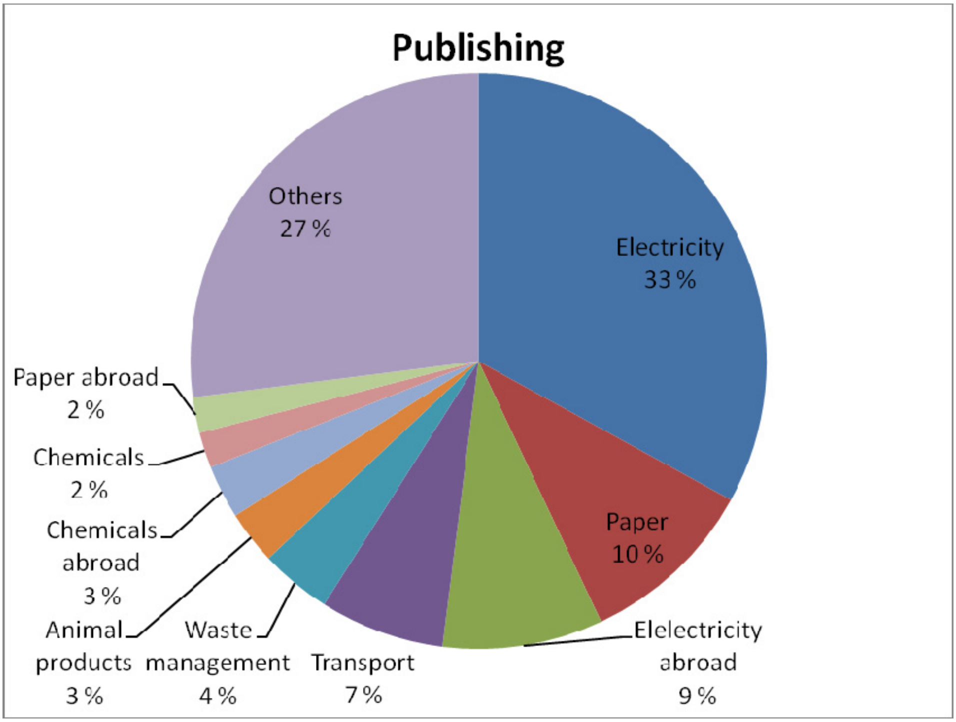

Figure 60. Sources of CO_2eq caused by the Finnish publishing sector (final products) in the ENVIMAT model.

The contribution of Publishing's final products to the life cycle climate impact of the entire Finnish economy was 0.39% and Printing's final products 0.15%. Thus their joint effect was 0.54%. It is worth mentioning that the contribution of these sectors includes only a very small share of the entire pulp and paper industry's contribution in Finland. In the pulp and paper sector, 98% of production is exported and thus cannot be included in the final products of Printing and Publishing produced and used in Finland.

The ENVIMAT results as such do not reveal the climate impact of the entire sector. That said, there is a method that enables the calculation of the total result of production, including both final and intermediate products; however, the results of the two sectors cannot be added together in this case due to overlaps. The carbon footprint can be calculated using the formula:

*Monetary output (€) of the sector *Specific emission coefficient (CO_2eq/€).*

For the Printing sector, the carbon footprint was *1700 M€ * 0.63 CO_2eq/€ = 1 072 000 tonnes CO_2eq* and for Publishing: *2707 M€ * 0.30 CO_2eq/€ = 813 000 tonnes CO_2eq*. in 2005. These results show that Printing supplies many intermediate products to Publishing (see Figure 4 and Table 3 in Chapter 2.3.2). It is well known that the sectors are strongly interlinked.

An analysis based on the first direct inputs (products or services) to each sector describes better how different the activities of the sectors are in practice (Figure 61 and Figure 62). The carbon footprints of the inputs are calculated by multiplying an input in monetary units with a specific emission coefficient of the input sector (kg CO_2eq/€).

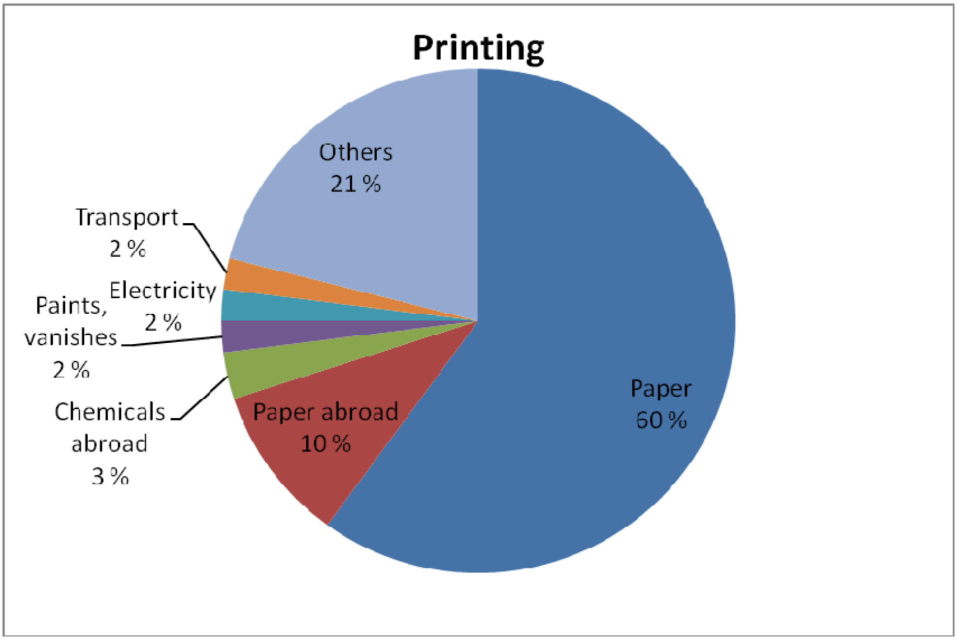

Figure 61. Distribution of CO_2eq of the direct inputs to the Finnish printing sector.

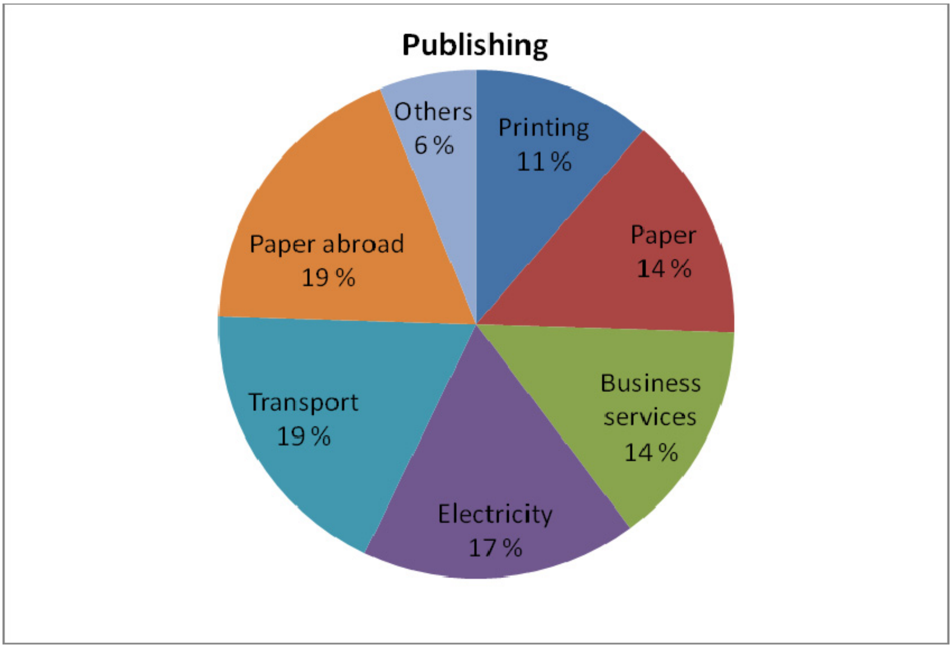

Figure 62. Distribution of the CO_2eq of the direct inputs to the Finnish publishing sector.

The climate impacts of the direct inputs are distributed quite evenly. It is noteworthy that in the Publishing sector's carbon footprint, Printing accounts for 11% of the direct inputs. Transport, paper from abroad, electricity and business services make the greatest contributions (Figure 62). The carbon footprint profile of Printing is naturally very different. Paper manufacturing dominates, followed by chemicals (Figure 61).

10.2 Impacts of printed products consumed by households in 2005 compared to the overall climate impacts of consumption

Statistics Finland investigates the expenditure of Finnish households annually. The results are presented by the classification of COICOP (Classification of Individual Consumption by Purpose). The environmental impacts of the consumption of households can be assessed by the ENVIMAT model based on the same classification. In COICOP, printed products are included in the category of Newspapers, books and stationery (CO95). All the other categories used in the

ENVIMAT model can be seen in Figure 63. The ENVIMAT model includes several environmental impacts, but only the climate impacts related to consumption of paper products are presented and discussed in this report.

The results describe actual individual consumption, abbreviated as AIC, including consumer goods and services purchased by households, in addition to services provided by non-profit institutions and general government for individual consumption, for example, health and education services. In other words, AIC covers all goods and services actually consumed by households (Eurostat). Housing (28%), foodstuffs (16%) and car driving (13%) caused the major part of the environmental impacts of actual individual consumption in Finland in 2005 (Figure 63).

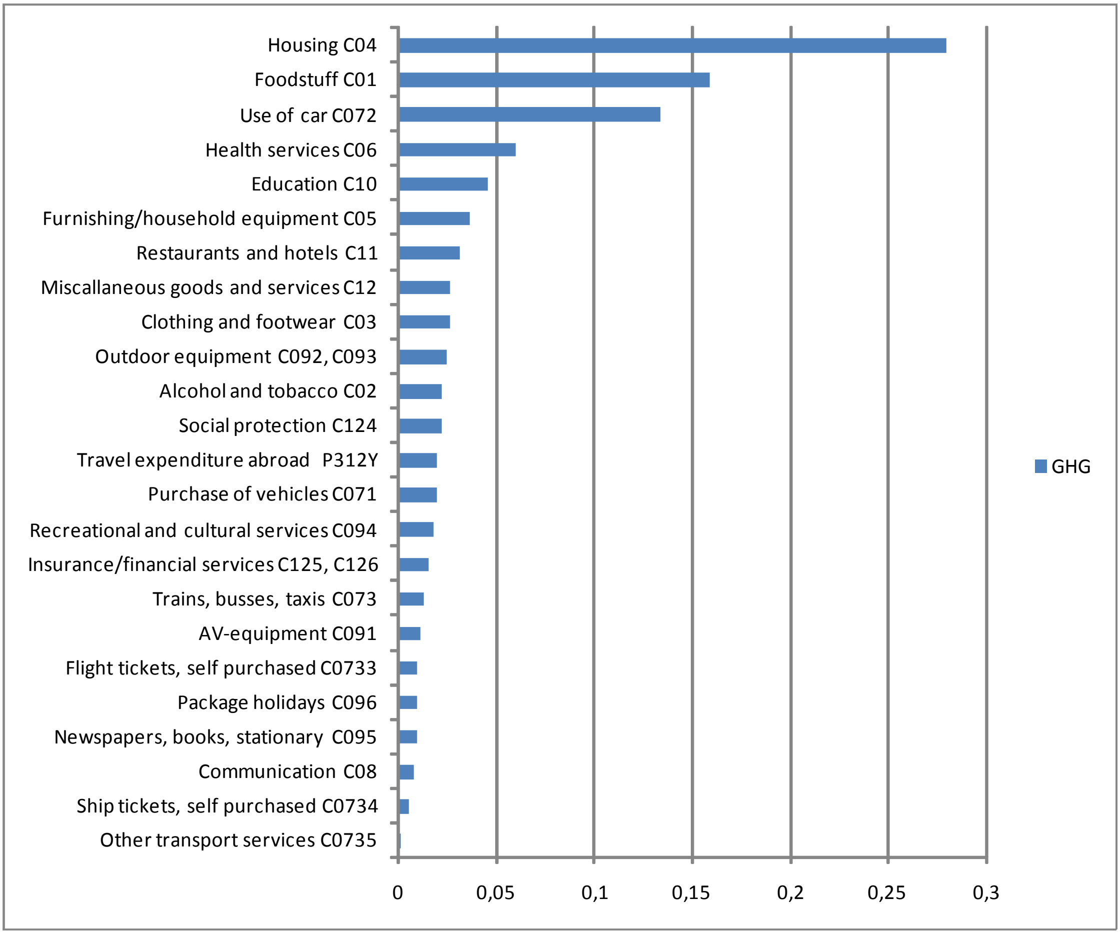

Figure 63. Climate impacts (GHG emissions) of actual individual consumption according to commodities in Finland in 2005. The values are normalized so that the value of the total impact is 1 (Seppälä et al. 2009).

Focusing on printed products, Finns spent EUR 1 331 million on purchases of newspapers, books and stationery in 2005. It is 1.29% of the entire consumption expenditure (Table 32). The contribution of these purchases to climate impacts is slightly lower, being 0.89%. A comparison of the impacts of the category CO95 to certain other categories, such as Operation of personal transport equipment (CO72) and Recreational and cultural services (CO94), shows that it has lower impacts than these other categories. The results are presented in Table 32.

Table 32. The climate impact of consumed newspapers, books and stationery by households and expenditure compared to some other COICOP categories in 2005. (COICOP = Classification of Individual Consumption by Purpose).

COICOP	CO_2eq. 1000 tonnes	Consumption expenditure M€
CO95 Newspapers, books, and stationery	**471**	**1 331**
Contribution to actual individual consumption expenditure of households	0.89%	1.29%
CO72 Operation of personal transport equipment	**7 072**	**4 623**
Contribution to actual individual consumption expenditure of households	13.4%	4.5%
CO94 Recreational and cultural services	**921**	**4 312**
Contribution to actual individual consumption expenditure of households	1.7%	4.2%

10.3 Conclusions

An environmentally extended input-output model, such as the ENVIMAT model, provides results for the final products at an aggregated level including several similar products, and thus does not indicate results for a single product. However, the ENVIMAT model can assess the magnitude of the contribution of printed products as a group via printing and publishing to the overall climate impact caused by the Finnish economy. The contribution of these two sectors totalled 0.54% in 2005: 0.39% for Publishing and 0.15% for Printing.

From the private consumption viewpoint, the highest contributors to climate impacts are housing (28%), foodstuffs (16%) and car driving (13%). The share of newspapers, books and paper products (stationery) is not very significant in this broad perspective. Only about 1% of the GHG emissions caused by the consumption of Finnish households originate from newspapers, books and paper products.

11. Conclusions and discussion

This chapter concludes the main findings based on the case studies and data collection conducted in the LEADER project (2007–2010). The usability of the results is evaluated and future development and research needs are discussed.

The objectives of the LEADER project were defined as follows:

- to create a holistic view of the environmental impacts of print products over their whole life cycle
- to utilize LCA (ISO 14040-44) and carbon footprint (e.g. PAS 2050) methodology and calculations to identify the critical life cycle stages and processes in which the emissions can be reduced
- to enable product-specific and/or manufacturing process-specific calculations with the evaluation of improvements on the European scale
- to highlight positive aspects of fibre-based print products and to discuss challenges related to different calculation tools and sustainability evaluation methods
- to evaluate and demonstrate new ways of presenting carbon footprint and LCA results.

During the project, data was collected concerning the whole life cycle of print products and five case products were selected for further study. Life cycle assessments were conducted and carbon footprints calculated for

- a regional newspaper (coldset offset printed)
- a weekly magazine (heatset offset printed)
- a photobook (printed with electrophotography).

Additionally, a carbon footprint study was conducted for

- an advertisement leaflet (rotogravure printed)
- hardcover book (sheet fed offset printed).

By selecting different case products, the potential impacts of different printing methods and different paper grades were included in the study. The case studies provide extensive examples of the environmental aspects and potential environmental impacts – and especially of the carbon footprints of printed products. Insofar as this was possible, the case studies were defined to present viable value chains that could exist in Finland.

Due to several differences between the case products (for example, the product properties, value chains and assumptions made), the results of the studies are not directly comparable. According to the principles of LCA methodology (ISO14040-44) only studies with similar system boundaries, main assumptions and functional units can be compared with each other. However, it can be stated that in addition to differences, the case studies point out many similarities and critical environmental aspects within the product group of fibre-based print products. Also the challenges related to the use of LCA and carbon footprint methodology to evaluate the environmental impacts of paper-based products have been illustrated and discussed in the context of the case studies.

11.1 Conclusions based on LCA case studies

Based on the case studies, it can be concluded that the use of energy and fuels dominates emissions and environmental impacts over the life cycle of print products. This impact is reflected in all LCI, carbon footprint and LCIA results and relates to all five case products. In the case of the magazine and newspaper, the highest potential environmental impact can be seen in the impact categories climate change, terrestrial acidification, particulate matter formation, fossil resources depletion and mineral resources depletion (Figure 64 and Figure 65 below). All these impacts relate to the use of energy and fuels in the product system.

In the case of the photobook (Figure 66), the highest potential impact category is freshwater eutrophication, followed by terrestrial acidification, fossil resources depletion, particulate matter formation and climate change. Compared to the magazine and newspaper cases, the potential impact in eutrophication is high and is due to the use of plastic wrapping as part of the photobook packaging. The eutrophication impacts from plastic wrapping are the result of high phosphorus emissions.

The central role of energy use underlines the need for continuous efforts to further improve energy efficiency in all stages of the life cycle in order to decrease environmental impacts. Indirectly, the use of energy can also be decreased efficiently by improving material efficiency in all processes. If the same amount of products can be produced from less material (for example by reducing the maculature percentage at the printing house), this also reduces the amount of energy inputs required for manufacturing the materials needed.

Additionally, the composition of both the energy production mix and the fuels used in the system has a great impact on the results. It can be stated that the results are highly sensitive to the energy production profile utilized. As a consequence, there may be big differences between similar products manufactured in different countries with the same technology and efficiency level. For example, the CO_2 equivalent emissions for the average Finnish five-year electricity production profile (applied in the case studies) amounted to approximately 250 kg CO_2eq/MWh whereas the same emission factor for European average energy in the Ecoinvent database is 500 kg CO_2eq.

The main results of the LCIA case studies for the newspaper, magazine and photobook are presented in Figure 64, Figure 65 and Figure 66. In the figures, one bar equals the entire system's impact in one impact category. The results were normalized (according to ReCiPe methodology) against the impacts caused by one European inhabitant during one year. This means that if for example the climate impact of one tonne of newspapers would equal the climate impact of one European per year, the value of the bar would be one. Normalized impact category results are dimensionless and enable the comparison of different impact category results against each other. In the figures, the life cycle phases "pulp and paper manufacturing" and "printing" include both the direct and indirect impacts of the life cycle phases (direct emissions from the site, manufacturing of raw materials and fuels and production of purchased energy).

In the newspaper and magazine case, seven impact categories were included in the assessment. In the photobook case, ten impact categories were included due to the availability of more extensive information related to emissions. (For more information about the impact categories see Chapters 2.1.4, 5.5, 6.6 and 7.4.)

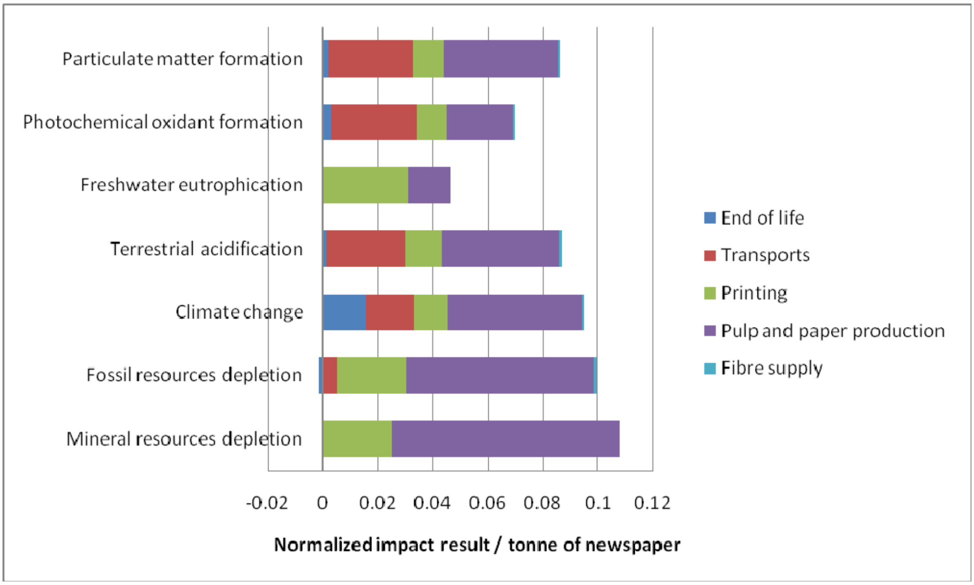

Figure 64. Environmental impacts of the life cycle of the newspaper (Basic case, higher emissions from landfill). One bar equals the entire system's impact in one impact category, in which the environmental impact of one European inhabitant per year = 1.

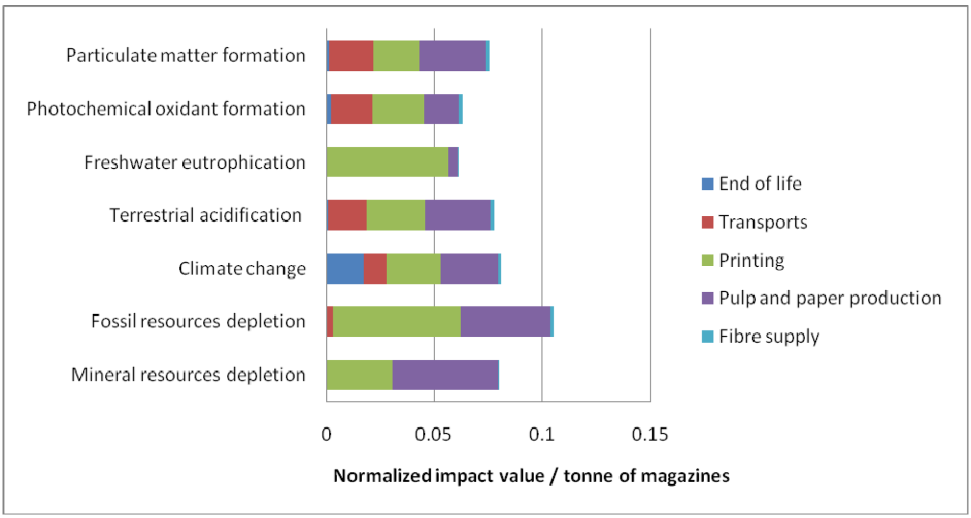

Figure 65. Environmental impacts of the life cycle of the magazine (Higher emissions from landfill, open loop allocation). One bar equals the entire system's impact in one impact category, in which the environmental impact of one European inhabitant per year = 1.

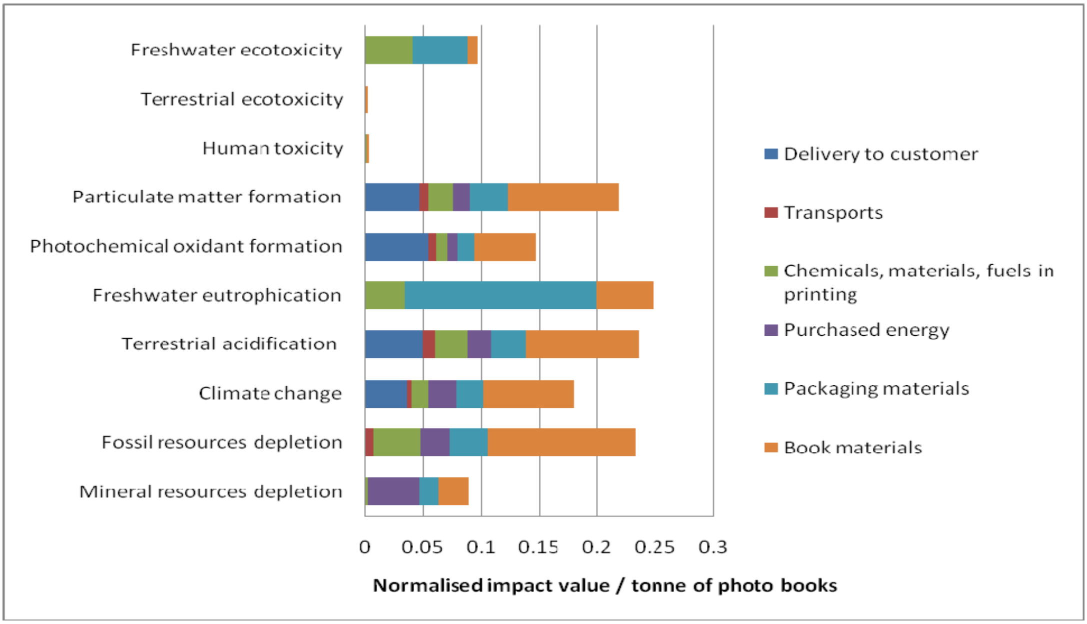

Figure 66. Environmental impacts of the photobook from cradle to customer. One bar equals the entire system's impact in one impact category, in which the environmental impact of one European inhabitant per year = 1.

11.2 Contribution of different life cycle stages

When considering the sources of potential emissions and environmental impacts, the biggest sources of emissions are the production of purchased energy for pulp and paper making and printing and transport. The large share of paper manufacturing in most impact categories is explained by the high share of paper in the end product. Paper is the substrate of all the case products and forms most of the weight of the end products. This is highlighted also in the case of the photobook, in which several paper grades and cardboard are used. The different fibre materials have similar impact profiles, but the overall amounts of impacts differ according to the different amounts of materials needed for the book.

The paper industry has made a concerted effort to decrease process energy consumption in different stages of the paper manufacturing phase, but further improvements are required in future. It should also be noted that the data applied in the case studies for different papermaking processes is typical process data and as such does not represent the best available technologies (BAT).

The contribution of the printing house to overall environmental impacts is also of importance. Improving energy and material efficiency in the printing process is an effective means of decreasing overall environmental impacts over the life cycle of print products. Based on the case studies it can also be concluded that the more complicated the print product is, the larger the share of the overall environmental or climate impact accounted for by the printing house. This can be seen when comparing the carbon footprint results from the magazine and newspaper cases with the carbon footprints of the sheetfed offset printed book and photobook (See Table 33). Sheetfed offset, bookbinding and electrophotography are processes operating at low speed and with small print runs. This is reflected as higher energy consumption, especially in the case of the sheetfed offset printed book.

Additionally, the use of solvents (in offset and rotogravure printing) causes VOC emissions that contribute to photochemical oxidant formation. According to the LCIA results, the use of fuels (propane in heatset offset), inks and chemicals in printing can have an impact on the overall environmental performance and carbon footprint of print products. The potential impacts of printing chemicals have been pointed out also by Larsen et al. (2006) in Denmark concerning a sheetfed offset printed product. As a consequence, the role of chemicals and fuels in printing requires further study and should not be neglected in future studies.

More surprising findings were the impacts related to paper disposed to landfill, the high share of home delivery in many air emission categories and the role of printing ink in the overall impacts. When disposed to landfill, paper decays and causes methane emissions. At the moment, the actual level of methane emissions created is not known exactly since both the decay rate and the collection rate of the landfill gas are difficult to measure. Because of this uncertainty, two different estimates and data modules related to landfill assumptions were used in the study: landfill with higher methane emissions and inefficient gas collection (LF high) and landfill with lower methane emissions and efficient gas collection (LF low) (see also Chapter 4.1.4). The landfill low module was designed for newsprint containing lignin but it was applied in all case studies due to the lack of more accurate data. The landfill high module was applicable to all paper grades.

The results contain uncertainty, but it was estimated that the actual situation in Finland would be somewhere between the results of these two modules. The results indicate that if a higher level of emissions occurs from paper disposed to landfill, the end of life has a significant contribution to the carbon footprint and to the climate impacts occurring during the whole life cycle of the product. This is the case even if it is assumed that only a relatively small portion of all newspapers or magazines (less than 20%) end up in landfill. With efficient gas collection and a lower level of methane emissions, the share of landfill emissions becomes minor when compared to the overall climate impacts.

Manufacturing of printing ink has not been extensively studied in the context of previous LCA studies concerning print products. Accurate data for different printing inks is difficult to find and thus an aggregated data module from the Ecoinvent database was applied in the newspaper, magazine and book cases. The data module represented a combination of different offset inks and included both mineral and vegetable oils. It was verified that the ink components included feasible components of offset inks. However, it is unlikely that exactly the same combination would be used, e.g. in a coldset offset or heatset offset printing process.

Based on the LCI and LCIA results acquired from the magazine and newspaper cases, the manufacturing of printing ink (for offset printing methods) is an area that requires further study to arrive at a real understanding of the impacts of printing ink as part of the print products life cycle. In Europe, the demand for priting inks is around one million tonnes per annum, and approximately 250 000 tonnes of the amount are offset inks. The consumption of vegetable oils in printing inks in Europe amounts to 80 000 tons yearly. (Fachgruppe Druckfarben 2010.) It was particularly surprising to note the high share of eutrophication impacts from the manufacturing chain of the partly vegetable oil-based printing ink when compared with the emissions from the paper making phase and considering the differences in the overall amounts of the raw materials used.

The assessment of the potential toxicity impacts of printing operations indicated high potential for both human toxicity impacts and terrestrial and freshwater ecotoxicity impacts from the production chains of the chemicals used in printing. Most of the toxicity impacts were due to metal emissions. High terrestrial ecotoxicity potential was also observed from herbicide and insecticide emissions originating in the production chain of printing ink. This, together with the observation that printing ink manufacturing may also cause high eutrophication impacts, stresses the need to closely study the overall impacts of mineral versus biobased materials. It is noteworthy that the toxicity assessment only partly covered the magazine life cycle due to data gaps, especially with respect to the chemicals and materials used in pulp and paper production.

In future, additional information would also be needed on the manufacturing of toner used in the electrophotography printing process and the circulation and refilling process of empty toner cartridges. Accurate data related to toner manufacturing is not publicly available and there is currently no information on the circulation and refilling of empty toner cartridges, a process that is handled by the toner manufacturer. Considering the growing markets of electrophotography printed products (such as photobooks and other print-on-demand products), there is an increasing need for this type of information.

In the case of the newspaper, magazine, photobook and advertisement, it was assumed that the product is delivered to the consumer (home delivery by mail or at night for newspapers). The potential impact of home delivery in the life cycle of products was significant and clearly bigger than the impact of other transport occurring during the product life cycle. This can be explained by the fact that home delivery is operated with small vehicles and only small amounts of products can be delivered at a time, which reduces the efficiency of the transport significantly. Additionally, the sparse population distribution in Finland affects the high environmental impact related to the home delivery phase. The share of transport (mainly due to home delivery) is particularly high in the impact categories particulate matter formation, photochemical oxidant formation, terrestrial acidification and climate change.

Based on the LCI, carbon footprint and LCIA results it can be stated that further optimization of transport (especially in the home delivery phase) is an important step in improving the overall environmental performance of these products. On the other hand, it should also be noted that home delivery is an essential aspect of newspaper and magazine products in Finnish culture since most of all the magazines (over 95%) and newspapers sold in Finland are ordered on subscription. For print-on-demand products, such as the photobook (of which only one or few copies of each product are printed), delivery by mail might still be much more efficient than driving a car to pick up the product from a certain outlet. Questions related to home delivery by mail and driving a car to pick up a book ordered from an internet bookstore have been discussed also by Borggren & Moberg (2009), and similar conclusions from Sweden were made.

11.3 Conclusions based on carbon footprint case studies

Based on the carbon footprint case studies, it can be stated that the results show that there is great variation between different print products. The results of the carbon footprint studies (from cradle to gate of the printing house) are summarized in Table 33.

Table 33. Carbon footprints of case products from cradle to gate (for one tonne and for one product).

Carbon footprint for one tonne of products from cradle to gate of the printing house		
Regional newspaper (coldset offset printed)	717 kg CO_2eq	
Weekly magazine (heatset offset printed)	593 kg CO_2eq	Open-loop allocation
Weekly magazine (heatset offset printed)	1141 kg CO_2eq	Avoided emissions
Photobook (electrophotography printed)	1341 kg CO_2eq	Without packaging
Photobook (electrophotography printed)	1609 kg CO_2eq	With packaging
Advertisement leaflet (rotogravure printed)	1253 kg CO_2eq	
Hardcover book (sheetfed offset printed	2322 kg CO_2eq	
Carbon footprint for one product from cradle to gate of the printing house		
Regional newspaper (coldset offset printed)	143 g CO_2eq Size: 200 g, 48 pages, broadsheet, 40 x 55 cm	
Weekly magazine (heatset offset printed)	101 g CO_2eq Size: 170 g, 56 pages, 22 x 30 cm	Open-loop allocation
Weekly magazine (heatset offset printed)	194 g CO_2eq Size: 170 g, 56 pages, 22 x 30 cm	Avoided emissions
Photobook (electrophotography printed)	671 g CO_2eq Size: 500 g, 64 pages, 21 x 30 cm	Without packaging
Photobook (electrophotography printed)	805 g CO_2eq Size: 500 g, 64 pages, 21 x 30 cm	With packaging
Advertisement leaflet (rotogravure printed)	25 g CO_2eq Size: 20 g, 4 pages, 40 x 50 cm	
Hardcover book (sheetfed offset printed)	1161 g CO_2eq Size: 500 g, 316 pages, 14 x 21 cm	

Based on the case studies and scenario analyses conducted, the carbon footprint results are very sensitive to system boundaries and assumptions (see also Figure 67). Thus the carbon footprints of different print products are not comparable with each other. Additionally, it is very difficult to provide information about a typical carbon footprint in the product group since the variation in results can be high. The variation also highlights the need for transparent reporting of the assumptions made and system boundaries. Background data is always needed to be able to interpret the result and evaluate the comprehensiveness of the study. As stated above in the context of life cycle assessment results, the energy production mix is in a very central role. Another central issue is the assumed size of the product. The more material is used, the higher the carbon footprint.

11.4 Challenges and development needs in carbon footprint and LCA methodology

Compared to other life cycle stages, the impacts caused by fibre supply are in a minor role. Potential environmental impacts of using renewable raw material (such as wood) are currently difficult to cover in LCA and carbon footprint methodology, and only emissions related to harvesting operations and saw mills were included in the study. New indicators and approaches are required to better evaluate the potential positive and negative impacts related to the use of renewable raw materials. There are methodological deficiencies in, for example, assessing the land use impacts in terms of loss of biodiversity and recreational values and degradation of landscapes. Impacts related to land use are important also when considering the renewability of the raw material in the case of sustainable forest management. Additionally, forests act as carbon sinks, which is a central issue when considering the potential climate impacts of paper products.

However, including biogenic carbon dioxide in carbon footprint calculations is challenging. The most relevant issues are the inclusion of the forest carbon balance and timeframe. Various approaches for including forest carbon sequestration in carbon footprint calculations have been presented, and at the moment, none of the published methods is internationally and scientifically recognized (for more information, see Chapter 2.2.4). According to PAS 2050 guidelines, carbon stored in the product can be calculated and credited if the lifespan of the product is longer than one year. In the LEADER project, the impact of carbon storage based on PAS 2050 was calculated in the case of the book and photobook. To conclude, it can be stated that a relatively long storage time should be expected for paper products before significant advantages can be gained.

Another critical aspect related to both life cycle assessment and carbon footprints of print products is the treatment of recyclable fibre produced in the system. Due to the high recycling rate of paper products, the product systems of magazine and newspaper produce a considerable amount of recyclable fibre. In the case of the magazine, 1100 kg of recycled fibre (maculature from the printing house and recycled magazines from consumers) is produced. Since magazines in this case are produced from primary fibre, none of the recycled material can be reutilized in the system. In the newspaper case, part of the recycled fibre can be used since the paper was assumed to include 60% recycled fibre.

According to LCA methodology, recycled fibre can be considered to be a by-product of the system which can be used as a raw material in another product system. Thus it is justified to allocate some of the environmental burdens to the recycled fibre produced. ISO 14040-44 standards recommend the use of system expansion to avoid actual allocation, but because several methods are possible in the magazine case and it is difficult to say that one is better than the other, the sensitivity of chosen allocation methods was studied.

The following allocation methods were applied in the magazine case study:

– **Cut-off allocation**, meaning that the system does not benefit from the recycled fibre that it produces. Cut-off allocation was used in the basic case.

– **Open-loop allocation**, meaning that a part of the emission load is allocated to the recycled fibre leaving the system, thereby providing benefits for the studied product system by producing raw material for another product system. The principles of open-loop allocation are presented in Appendix G. In this study, 63% of the inputs and outputs from paper manufacturing are allocated to the recycled fibre that is produced in the system. It should be noted that only the inputs and outputs of paper production are allocated, and printing and end of life are allocated in full to the studied magazine.

– **System expansion with avoided emissions** is another way to calculate the benefits from producing raw materials to another product system. In Finland, it is typical for most of the recycled fibre (from magazine and newsprint recycling) to be used in newsprint manufacturing. In this study, recycled fibre was assumed to be used in newsprint manufacturing, thereby avoiding the production of thermomechanical pulp (TMP). By means of system expansion, electricity-intensive TMP production can be avoided. On the other hand, the TMP process would produce heat as a by-product and this heat production is also avoided and needs to be replaced by additional heat production. In this study, it is assumed that heat produced in the TMP process replaces average Finnish heat production and when the TMP process is replaced by deinking, more average Finnish heat needs to be produced.

The carbon footprint results for the magazine with different allocation methods are presented in Figure 67. Figure 67 presents high variation between the different scenarios. Different allocation methods for recycled fibre lead to totally different carbon footprints. Open-loop allocation reduces the carbon footprint remarkably (by 40%) compared to the unallocated (cut off) and system expansion (avoided emissions) cases. In the case of open-loop allocation, it is considered that 40% of the carbon footprint is transferred to the other product system using the recycled fibre as an input for new products. Similar results were also received concerning other emissions to air, emissions to water and life cycle impact assessment. Allocating part of the emission load to the recycled fibre leaving the system decreases the amount of paper a printing house needs to produce one tonne of magazines. Thus all impacts generated in pulp and paper production and all the preceding life cycle phases are reduced. (See also Chapter 6.6.)

The results of the scenario analysis in the magazine case indicate the challenges in treating the recyclability of the raw materials in LCA methodology and once again show that the system boundary has a strong influence on the LCA results. The results of the system expansion (avoided emissions) scenario point out that the positive impacts of recycling are not easy to assess extensively. Paper recycling saves virgin wood and this saved wood can either be left in the woods where it acts as a carbon sink or used for other purposes such as energy production. This biobased energy can in turn replace fossil-based energy. Altogether this means that the consequences of paper recycling extend to systems outside of the product system modelled here, and thus the savings on emissions and impacts achieved by paper recycling can be much higher than our calculations (in the avoided emissions scenario) reveal.

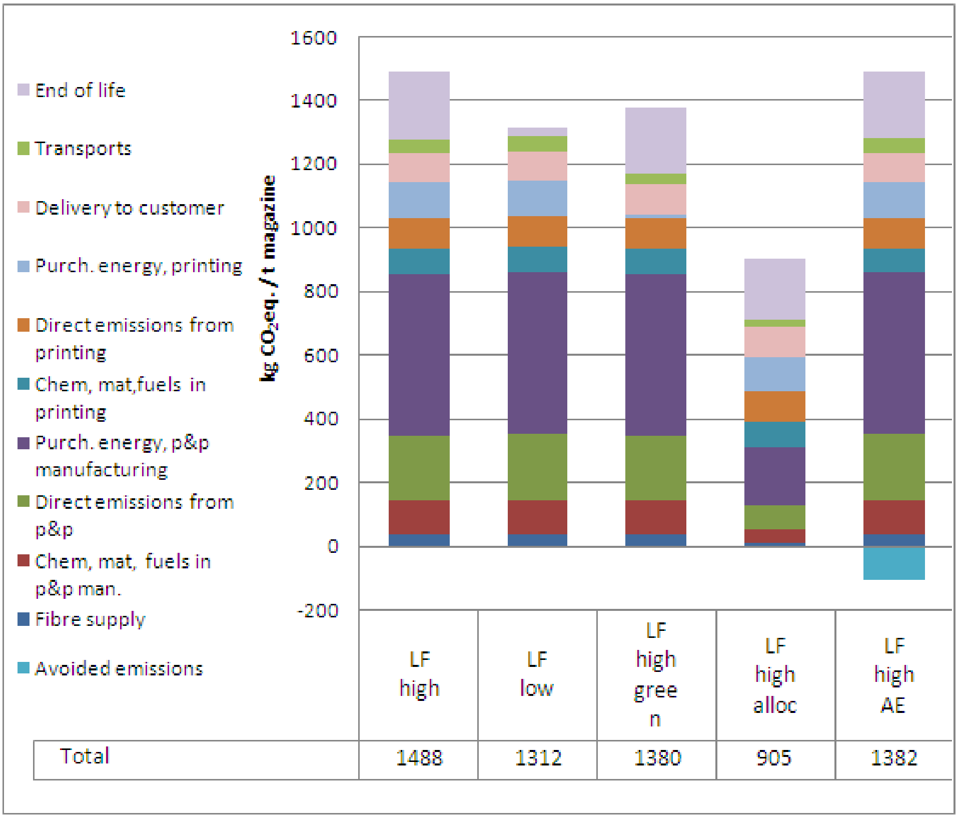

Figure 67. Carbon footprint for one tonne of magazines (air dry tonne) in different scenarios. Bars from left to right: 1) basic case (no allocation) with higher landfill emissions, 2) basic case (no allocation) with lower landfill emissions, 3) higher landfill emissions and green electricity in the printing house (no allocation), 4) higher landfill emissions and open-loop allocation of recyclable fibre, 5) higher landfill emissions and avoided emissions from production of recyclable fibre. Note: avoided emissions are not subtracted from bar five and can be seen below the bar.

Finally, it should also be noted that the LCIA does not cover all environmental impacts potentially caused by the life cycle. There are methodological deficiencies in, for example, assessing the impacts of odour and noise. Additionally, the toxicity and ecotoxicity assessment in the LCIA framework is still under development. There are major uncertainties connected to the toxicity impacts of metals in particular. Metals form different types of compounds in different environmental conditions and the toxicity of compounds varies. In the LCIA, our knowledge of the environmental conditions in which metal emissions occur is not detailed enough and thus we do not know what types of compounds the metals form. In this study, assessment of potential toxicity and ecotoxicity impacts was not conducted extensively due to lack of data on metal emissions. Thus, this is an area that should be better covered in future studies in order to arrive at a better understanding of potential toxicity impacts over the life cycle of print products.

Another aspect that is not yet covered in the life cycle impact assessment is the mineral resource depletion impact from the use of limestone for pigment manufacturing. The emissions related to mining activities and manufacturing of limestone are included in the LCI, but in the LCIA methodology the use of limestone resources is currently not included in the impact category mineral resources depletion. This is due to limited data related to availability of mineral resources on earth. Limestone is used for example in the manufacturing of $CaCO_3$ that is used as pigment in LWC paper manufacturing. Depending on the paper grade, the share of pigments can be relatively high (in the case of LWC paper more than 30%). As a consequence, including the impacts from the use of limestone would be important in covering the overall environmental impacts of paper manufacturing.

11.5 Evaluating the magnitude of the carbon footprint and environmental impacts of print products

In the context of different case products, the size of the carbon footprint of one tonne, one product and one print run were presented in relation to greenhouse gas emissions created by driving a car, electricity used in watching a modern TV and electricity and heat used for typical Finnish houses and apartments (see Chapters 5.6, 6.7, 7.5, 8.3 and 9.4). These values were calculated to evaluate the magnitude of the carbon footprints of different print products and also the overall carbon footprint of print runs.

In addition to product-based life cycle assessment and carbon footprints, the environmentally extended input-output model ENVIMAT (Seppälä et al. 2009) was applied to gain an understanding of the climate impacts of the print products in general, at the product category level. To be able to evaluate the magnitude of the carbon footprints of different products, comparable information is often required. This information is important for evaluating whether the impact of one product is high or low. Since the direct comparison of different studies and products is extremely difficult, and comparable information is seldom available, the ENVIMAT model was applied to gain an understanding of the impacts of paper-based print products in relation to the overall climate impacts of Finnish production and consumption. (For a description of the ENVIMAT model, see Chapters 2.3 and 10.)

An environmentally extended input-output model, such as the ENVIMAT model, provides results for the final products at an aggregated level including several similar products, and thus does not indicate results for a single product. However, the ENVIMAT model can assess the magnitude of the contribution of printed products as a group via printing and publishing to the overall climate impact caused by the Finnish economy.

Based on the ENVIMAT model, the carbon footprint of the final products of Publishing was 489 000 tonnes CO_2eq and that of Printing 181 000 tonnes CO_2eq in 2005 (classification of the Printing and Publishing sectors is presented in Chapter 2.3.1). The results are composed of all the final products the sectors produced in Finland, but not their intermediate products that, according to the principle of life cycle thinking, belong to other product chains.

The contribution of Publishing's final products to the life cycle climate impact of the entire Finnish economy was 0.39% and Printing's final products 0.15%. Thus their joint effect was 0.54%. It is worth mentioning that the contribution of these sectors includes only a very small share of the entire pulp and paper industry's contribution in Finland. In the pulp and paper sector, 98% of production is exported and thus cannot be included in the final products of printing and publishing produced in Finland.

From the private consumption viewpoint, the highest contributors to climate impacts are housing (28%), foodstuffs (16%) and car driving (13%). The share of newspapers, books and paper products (stationery) is not very significant in this broad perspective. Only about 1% of the GHG emissions caused by the consumption of Finnish households originate from newspapers, books and paper products. (See also Chapter 10.2.)

The results of the ENVIMAT model reveal that in comparison to the overall climate impacts of private consumption (households) in Finland, paper-based print products are not in a very significant role. On the other hand, the paper industry in Finland is among the biggest users of energy and biggest emitters of greenhouse gas emissions. However, this is due to the high production rates of paper in Finland (see also the Preface). Because more than 90% of all the produced paper is exported to other countries, the overall production and consumption figures of the industry in Finland do not accurately reflect the actual impacts at product or product category level.

It should be noted that in this report, the ENVIMAT model was applied only for the evaluation of climate impacts related to print products. However, the results of the LCIA (where other environmental aspects and impacts have been considered) also point out that the impacts of manufacturing one tonne of newspapers, magazines or photobooks are not very high in relation to the environmental impacts caused by one European inhabitant per year.

The share of the environmental impacts caused by one yearly newspaper subscription (yearly edition 356 issues) from the impacts of one tonne of newspaper is presented in Figure 68. In the figure, the value of the environmental impact of one European inhabitant per year is 1. This means that if for example the climate impact of one tonne of newspapers would equal the climate impact of one European per year, the value of the bar would be one.

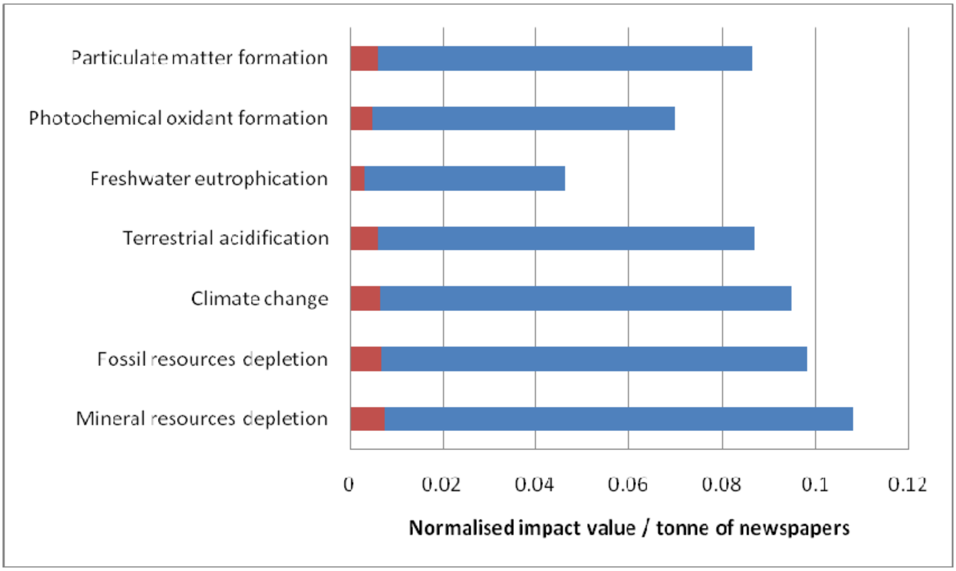

Figure 68. The share of one yearly subscription (red bar) of the impacts of one tonne of newspapers (whole bar). Environmental impact of one European inhabitant per year is 1.

When considering the LCIA results, it is good to remember that in Europe, the average annual consumption of paper products is approximately 155 kg per person. An average Finnish person consumes approximately 230–240 kg of paper products per year (Finnish Forest Industries Federation 2010). One yearly newspaper subscription weighs approximately 70 kg and thus one tonne of newspapers is approximately equivalent to a 14-year subscription (or 4984 newspaper issues).

As a conclusion, the environmental impacts and especially the climate impacts of print products (at product and product category level) are not very high compared to the overall environmental impacts caused by daily living. On the other hand, paper-based products are often daily products with a rather short lifespan and their overall production rate is very high. In Finland the forest industry produces around 11 million tonnes of paper and paperboard annually. The bulk of the produced paper and board is exported (over 90%). (Finnish forest industries federation 2009a.) At the Western European level, paper and paperboard production in 2009 was around 83 million tonnes, of which newsprint accounted for 11%, woodfree graphic paper for 19%, mechanical graphic paper for 17%, packaging paper and board for 42% and other paper and board for 11% (CEPI 2009).

Due to the high production amounts, the overall impacts caused by the industry on a regional level can be significant. Therefore, even small improvements in the environmental performance at product level (that might not seem very significant when considering the impacts of one product or one tonne) are important and can lead to significant improvements in overall resource use and environmental impacts. (See also Chapter 11.4.)

To conclude the main findings of the LEADER project, a combination of different environmental aspects, potential impacts and methodologies is required to enable the evaluation of the overall environmental impacts caused by paper-based print products. Mitigating climate change is an urgent issue that requires action from all actors in the print media value chain. Carbon footprinting can be a useful tool in evaluating the amount and sources of GHG emissions created. However, it is not enough to use only carbon footprints as an indicator of product sustainability. Other aspects need to be included, for example by using the life cycle assessment methodology.

Additionally, as much as possible, the potential impacts should be considered by taking into account different levels of action:

- product level
- product category level
- company and/or industry level
- regional level.

To enable the evaluation of impacts at different levels, it is likely that a combination of different evaluation tools is required. In this project, the product-based LCA was combined with the ENVIMAT model, which operates on an aggregated level based on data from national and international statistics.

Presenting the results in relation to other product groups or competing results remains challenging due to the relative nature of the LCA methodology (see Chapter 2). The development of climate labels aims to produce comparable information for consumers on the climate impacts of different products. Development of methodologies is required before this can be transparently achieved. On the other hand, when more comprehensive LCA results from different product groups become available, this will also enable the development of transparent and fair criteria for comparison that could be used as a basis for climate labels. Availability of such criteria could greatly improve the possibility of both consumers and producers to make decisions that help reduce GHG emissions and mitigate climate change.

11.6 Usability of the results

It is hoped that the results of the LEADER project could be used as reference and background information when further developing methodologies and calculation principles suitable for fibre-based print products. To increase the usability of the results, special attention has been given to reporting both the results and the assumptions made as transparently as possible. Transparent reporting is essential for interpreting the results since the results are extremely sensitive to the assumptions and system boundaries due to the relative nature of the LCA methodology. This sensitivity has been highlighted in the results of the case studies by calculating several scenarios and evaluating different methodologies to treat the production of recyclable fibre (allocation and system expansion), applying different energy production profiles and different assumptions and data modules for the end-of-life phase (GHG emissions from landfill).

In addition, one of the goals of the project was to provide information about the environmental impacts occurring during different stages of the product life cycle. In all cases, the results of the LCI, carbon footprint and LCIA were reported divided into life cycle stages and considering both direct and indirect emissions and impacts (such as the direct emissions from the paper mills and printing houses and the emissions from the production of purchased electricity and raw materials). By presenting the sources and potential impacts according to life cycle stages, the results can be used by the actors of the print media value chain in analyzing the phases that have the greatest reduction potential. Additionally, the influence of different actors over the impacts of the whole life cycle can be evaluated.

In the case of the newspaper, magazine and rotogravure printed leaflet, the life cycle of the product was followed from cradle to grave. In the case of the photobook and hardcover novel, the life cycle was studied up to the consumer (end-user) and retailer. At the time of writing, not many comprehensive LCA or carbon footprint studies (covering the whole life cycle) for print products have been publicly available. As a consequence, it can be stated that case studies provide new information about the potential environmental impacts related to print products. Especially the end-of-life treatments, all transport and manufacturing of printing ink and printing plates are aspects that have not been studied widely before.

Challenges related to communicating the environmental impacts of products are discussed in the independent second part of the LEADER report (see Pihkola et al. 2010). Qualitative research focusing on the needs and challenges related to communicating the environmental impacts and carbon footprints of print products was conducted based on interviews with the actors in the print media value chain. Additionally, the report includes a literature review of available guidelines and tools for product-based communication and presents the development process of communication materials (fact sheets) that summarize the results of the case studies described in report 1.

11.7 Monitoring the environmental sustainability of printing

The development and monitoring of environmental indicators specific for printing houses were discussed in Chapter 3. The findings point out that in Finland the environmental sustainability of conventional printing has mainly improved over the last decade. This is partly explained by technology improvements but also by legislation, systematic efforts and better knowledge of the importance of environmental issues. However, it should be noted that the evaluation is made at quite a coarse level simply because of several differences between the data sources and data processing.

A clear decline has been seen in the energy, ink and chemicals consumption of conventional printing houses (CSWO, HSWO, SFO and Gravure), while paper consumption has stayed at the same level. Furthermore, the improved sorting of waste and decreased amount of landfill waste are a positive development. Based on the LCI data and literature collected, it seems that on many occasions, continuous efforts to improve the environmental performance of printing have brought good results.

However, a constant challenge for printing houses is the growing need for information concerning the environmental performance of products. The evaluation of indicators at printing houses (e.g. energy and material consumption) facilitates monitoring the state and progress of values concerning environmental performance. Indicators that are specific to the product group or product are even more essential.

During the data collection phase it was noted that there is a need for monitoring devices and reporting systems that would help printing houses to more accurately follow production and related environmental data (for more information, see Chapter 3). Although developing product-specific indicators is a labourious process, they are worth the effort; they will give precise information about the products, help to find critical phases and to do calculations throughout the whole value chain (e.g. carbon footprint calculation). In addition, they make it possible to communicate the information internally and in B-to-B and consumer relationships.

Undoubtedly, new technology has a significant influence on the environmental performance of printing. However, it is also important how the operating and manufacturing procedures are carried out as well as how the new technology is used. During the research it was found that, for instance, turning off digital printing machines for the night and optimizing air cooling can potentially decrease energy consumption and environmental load. It was also discovered that systematic devices, displays and reporting systems can help in gathering detailed information about energy and material consumption. Thus, the possible reduction points of emissions in the manufacturing of print products can be identified more easily.

11.8 Discussion

Like LCA, carbon footprint calculations involve choices and conditions that influence the final result. System boundaries, allocation methods and data coverage and quality can change study conclusions. Therefore it is extremely important to follow internationally accepted guidelines and build the assessment grounds to match the goal and scope of the study. However, even when applied, the standards leave room for choices. Therefore transparency is a key word, especially when conducting carbon footprint calculations for comparative purposes. These issues become less critical when applying carbon footprint studies for product and process development. Even though carbon footprinting is currently often regarded as a way to communicate to stakeholders and argue in environmental debates, its role in product development should not be underestimated. After all, it is one of the most important ways of reducing climate impacts and mitigating climate change.

Biogenic carbon raises questions when calculating carbon footprints for paper products. Currently biogenic carbon is regarded as neutral but if the carbon is stored in a product for a longer period of time, reductions can be calculated. However, several universities and scientists are researching the influence of the change in the forest carbon balance on the carbon content in the atmosphere. Thus far the results are confusingly conflicting and product-based applications seem difficult to model (see Chapter 2.2.4).

The comparability of different results continues to be a challenge, and transparency remains important. For example, to date, a full LCA comparing electronic and print media has not been completed. Among the biggest challenges in the comparison are questions related to the functional unit and different supply chains of the products. The question of defining the correct functional unit has been discussed e.g. by Moberg (2010) and (Reichart & Hischier 2003). One of the main challenges is that the functional unit should also describe the benefit received from reading a printed newspaper or reading the same information from the internet with a computer or an electronic reading device. But the benefit received by different persons is a highly subjective issue and is difficult to measure in a standardized way.

Additionally, the screening LCA studies made in Sweden (Moberg 2010; Moberg et al. 2010) point out, for instance, that there are still data gaps concerning electronic media products (e.g. manufacturing of components and recycling of products) and allocation concerning the distribution of electronic content. Additionally, the Swedish comparison of a printed book and an electronic book read from an e-reader showed that the impacts of the two product systems are quite different.

The paper book had a higher contribution to resource use, global warming, energy demand, eutrophication, human toxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity. The e-book had a higher contribution to acidification, ozone depletion, freshwater aquatic ecotoxicity and photochemical ozone creation. (Borggren & Moberg 2009.)

In this context it should also be noted that the energy efficiency of the new e-reading devices seems to be remarkably better than that of computers and is likely to improve in the future. This will probably make the comparison even more challenging from the point of view of print products.

Besides carbon footprinting, the development of the water footprint has recently started. The water footprint is a new indicator that focuses on the overall use of water in the life cycle of products. The development of the water footprint concept originally started based on the work of Arjen Hoekstra (see e.g. Hoekstra & Chapagain 2008), which focused mainly on the water footprint of nations. Currently, the development of the water footprint for products is under development and the preparation of ISO 14046 Water footprint – Requirements and Guidelines is ongoing. It is likely that the water footprint standard will include many interfaces with both the ISO 14040-44 LCA standards and the coming ISO 14067 Carbon footprint standard.

The quality, adequacy and depletion of fresh water resources is a global area of concern. As part of their product responsibility, all companies should be prepared to discuss and to reduce their use of water in the future. The use of water was not studied in the LEADER project but it was noted that although water use is already monitored by several companies within the print product value chain, the calculation of water footprints will demand information that is not yet easily available. Thus, water consumption is one of the aspects that requires more attention within the actions of the graphic arts industry and future research.

12. Summary

This report presents the main results of the LEADER project that was ongoing in Finland between the years 2007–2010. The aim of the project was to study the environmental impacts occurring during the life cycle of print products. The scope of the project was focused on printed media products.

In the study, life cycle assessments were conducted and carbon footprints were calculated for three case products:

- coldset offset printed newspaper (Chapter 5)
- heatset offset printed magazine (Chapter 6)
- electrophotography printed photobook (Chapter 7).

Additionally, a carbon footprint case study was conducted for two case products:

- rotogravure printed advertisement leaflet (Chapter 8)
- sheetfed offset printed book (Chapter 9).

The case studies provide extensive examples of the environmental aspects and potential environmental impacts – and especially of the carbon footprints – in the group of printed products. Insofar as this was possible, the case studies were defined to present viable value chains that could exist in Finland.

In the cases of the magazine, newspaper and rotogravure printed leaflet, the life cycle of the product was followed from cradle to grave. In the cases of the photobook and sheetfed offset printed book, the life cycle was studied until consumer or retailer. In all cases, the distribution (transport) of products until end user or retailer was included in the study.

In the life cycle impact assessment case studies, both the life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases were included. In the LCI, main emissions to air (NOx, SO_2, TSP and VOC) and main emissions to water (COD, Ptot, Ntot, TSS, AOx) were reported. All greenhouse gas emissions were included and reported in the carbon footprint as carbon dioxide equivalents.

Depending on the case product, the carbon footprint for one tonne of products (from cradle to gate) varied from 700 kg to 2300 kg CO_2 equivalents. In addition, the variation within the same case can be high, depending on the assumptions made. For the composition of the carbon footprint, the most significant issues are the applied energy production mix (for purchased energy and fuels used), the assumed type of production (for example, a printing process operating with high or low speed and/or volumes), size of the product, assumptions related to the distribution of the product and end use. Especially the assumed level of methane emissions from paper disposed to landfill might have a significant impact on the overall carbon footprint. However, the methane emissions from the landfill involve uncertainty because the actual amount of emissions created at landfill is not known.

For the photobook and sheetfed offset printed book, the carbon stored in the product was also calculated according to the PAS 2050 guidelines. In the case of the SFO printed hardcover book, the assumed storage times were 5, 50 and 100 years. As a conclusion, it can be stated that for paper products, a rather long storage time needs to be expected before considerable benefits or credits are created. By following the principles of PAS 2050, the carbon credit for the storage of a book for five years is 5% of the total carbon footprint. When the book is stored for 100 years, the total carbon content of the product can be credited from the carbon footprint, and the credit increases to 75% of the total carbon footprint. For other case products, the assumed lifespan was less than one year and thus the carbon storage was excluded from the study.

The results of different case studies are not comparable, and it is difficult to provide information about a typical carbon footprint in the product group. Background data is always needed to be able to interpret the result and evaluate the comprehensiveness of the study. Like LCA, carbon footprint calculations involve choices and conditions that influence the final result. System boundaries, allocation methods and data coverage and quality can change study conclusions. Therefore it is extremely important to follow internationally accepted guidelines and build the assessment grounds to match the goal and scope of the study. However, even when applied, the standards leave room for choices. Therefore transparency is a key word, especially when conducting carbon footprint calculations for comparative purposes.

Despite these limitations, carbon footprinting can be a useful tool in evaluating the amount and sources of GHG emissions created. However, it is not enough to use only carbon footprints as an indicator of product sustainability.

Other aspects need to be included, for example by using the life cycle assessment methodology.

The LCIA was performed using the ReCiPe Mid/Endpoint method (version November 2009) (Goedkoop et al. 2009). The LCIA results were normalized against the environmental impacts of one European inhabitant per year. Even though the results of different case studies are not comparable, several common aspects can be found from the cases. To sum up the main findings related to all five cases, the use of energy and fuels dominates emissions and environmental impacts over the life cycle of print products. In the cases of the magazine and newspaper, the highest potential environmental impact can be seen in the impact categories fossil resources depletion, mineral resources depletion, terrestrial acidification, particulate matter formation and climate change. All these impacts relate directly to the use of energy and fuels in the product system.

In the case of the photobook, the highest potential impact category is freshwater eutrophication, followed by terrestrial acidification, fossil resources depletion, particulate matter formation and climate change. Compared to the magazine and newspaper cases, the potential impact in eutrophication is high and it is due to the use of plastic wrapping as part of the photobook packaging.

Due to the central role of energy and fuels, improving energy efficiency in all stages of the life cycle is an efficient way to decrease environmental impacts. In addition, the composition of the energy production mix and the fuels used in the system has a great impact on the results.

When considering the sources of emissions and environmental impacts, the biggest sources of emissions are the production of purchased energy for pulp and paper making and printing and transport. The large share of paper manufacturing in most impact categories is explained by the high share of paper in the end product. The contribution of the printing house to the overall environmental impacts is also of importance. In the case studies, the share of the total carbon footprint (from cradle to grave) accounted for by the printing phase (in total) varied between 13–46% depending on the case (newspaper, magazine, photobook or book). The share of carbon footprint related to paper manufacturing phase (in total) varied between 33–55% of the total amount. Improving energy and material efficiency in the printing process is an effective means of decreasing the overall environmental impacts over the life cycle of print products. Based on the case studies it can also be concluded that the more complicated the print product is, the larger the share of the overall environmental or climate impact accounted for by the printing house.

More surprising findings were the impacts related to paper disposed to landfill, the high share of home delivery in many air emission categories and the role of printing ink in the overall impacts. Manufacturing of printing ink (for offset printing methods) is an area that requires further study to arrive at a real understanding of the impacts of printing ink as part of the print products life cycle. It was particularly surprising to note the high share of eutrophication impacts from the manufacturing chain of the partly vegetable oil-based printing ink. Additionally, more information would be required about the manufacturing of toner used in electrophotography printing.

The environmentally extended input-output model ENVIMAT was applied to provide an estimate of the environmental impacts related to the production and consumption of print products in Finland. From the private consumption viewpoint, about 1% of the GHG emissions caused by the consumption of Finnish households originate from newspapers, books and paper products. The highest contributors to climate impacts are housing (28%), foodstuffs (16%) and car driving (13%).

The contribution of Publishing's final products to the life cycle climate impact of the entire Finnish economy was 0.39% and Printing's final products 0.15%. Thus their joint effect was 0.54% (classification of the Printing and Publishing sectors is presented in Chapter 2.3.1). The results are composed of all the final products the sectors produced in Finland, but not their intermediate products that, according to the principle of life cycle thinking, belong to other product chains. The contribution of these sectors includes only a very small share of the entire pulp and paper industry's contribution in Finland. In the pulp and paper sector, 98% of production is exported and thus cannot be included in the final products of printing and publishing produced in Finland.

As a conclusion, the environmental impacts and especially the climate impacts of print products (at product and product category level) are not very high compared to the overall environmental impacts caused by daily living. On the other hand, paper-based products are often daily products with a rather short lifespan and their overall production rate is very high. Due to high production amounts, the overall impacts caused by the industry on a regional level can be very significant. Therefore, even small improvements in the environmental performance at product level are important and can lead to significant improvements in overall resource use and environmental impacts. For example, following product group- or product-specific indicators systematically in print product manufacturing will provide valuable information in the field of sustainability and possible improvements in it.

To enable the evaluation of the overall environmental impacts caused by paper-based print products, a combination of different environmental aspects, potential impacts and methodologies is required. Additionally, the potential impacts should be considered, taking into account different levels of action.

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Appendix A: The calculation principles for environmental indicators in Chapter 3

The data values for the environmental indicators for printing (presented in Chapter 3, table 4) were calculated and estimated in the following way. **All the figures were presented in terms of tonne of printed products.**

1) The **energy consumption figures** are focused on the energy used for manufacturing print products. However, this was sometimes very difficult because of the lack of exact figures and in these cases a realistic estimation was made. On the other hand, at some printing houses the energy use of printing processes was measured during the research. Thus in some cases it was possible to obtain more exact information than in the others.

2) The estimation of **paper consumption** in tonnes / year: It was calculated based on the different paper grade amounts ordered by the printing house during a year. All the paper maculature and waste during the production year were extracted from this figure.

3) The **ink consumption in tonnes / year** was estimated based on ink ordered by the printing house during a year. All the ink waste during the production year was extracted from this figure.

   Based on the ink consumption and paper consumption estimates above, it was possible to sum up and do the estimation of **the print production in tonnes / year**, which was used as a divisor.

4) **VOC emissions** were in some cases based on measurements and in some cases they were estimated and calculated based on the chemicals used (kg) during the year by the printing house and the information of safe usage brochures concerning the amount of isopropanol in the product.

5) The total waste amount was estimated based on the detailed information gathered on different kinds of waste fractions such as landfill, electronic, metal, hazardous (ink), energy (plastics, wood) and recyclable waste (aluminium, paper) at each printing house. **The percentage of material for recycling and recovery use** was calculated based on the data collected. Furthermore, the amount of **hazardous waste (kg/tonne)** was calculated.

Appendix B: Summary of technical and process improvements in printing processes

Summary of the technical and process improvements and their impact on various environmental aspects during fifteen years (XX = strong positive influence, X = moderate positive influence).

Technical development	Improved energy efficiency	Improved materials efficiency	Reduced VOC emissions	Reduced waste output	Application
Direct drives replacing shafts and belt transmission, inverts, improved ink drying	xx				All conventional methods
Optimized blanket compression, optimized surface properties of blankets and rollers to reduce cleaning solvent need	x		x		Offset
Improved cooling and ventilation; heat recovery	xx				All conventional methods
Regenerative thermal oxidation of dryer exhaust gas; dryer-integrated incinerators	xx	x	x		HSWO
Digital prepress and CTP eliminating film exposure and processing chemicals	x	xx		X	All conventional methods
Chemistry-free and process less plates	x	x		X	Offset
Toner development for smaller particle size and lower fixing temperatures	xx	x			Electrophotography
Machine configuration and technology development	xx	x	x	X	Electrophotography
Ink development for lower solvent content and smaller pigment size	x	xx	xx	X	Inkjet
Make-ready automation	x	x	x	X	All presses
Closed loop color control		xx		X	All methods
Automated ink and fountain solution supply and processing	x	xx	x	X	All methods
Automatic press cleaning devices	x	x		X	Offset
Optimized paper grades and properties		x			All methods
Reduction and substitution of chemicals with low VOC ones		x	xx		All methods
UCR and GCR techniques		x			All methods
Improved waste sorting, processing and management	x	x	x	Xx	All methods

Appendix C: Energy modules used in the study

Both Finnish and European electricity mixes are used in the study. In most of the cases, the geographical scope was Finland and therefore an average Finnish grid mix was used in the study. Because the emission factor of electricity is highly dependent on the annual changes (e.g. due to the available amount of hydropower), a five-year average was calculated to diminish the impact of annual variations. Five-year electricity mix emits approximately 250 kg CO_2eq/MWh. Figure C1 presents the electricity production mix used in the study.

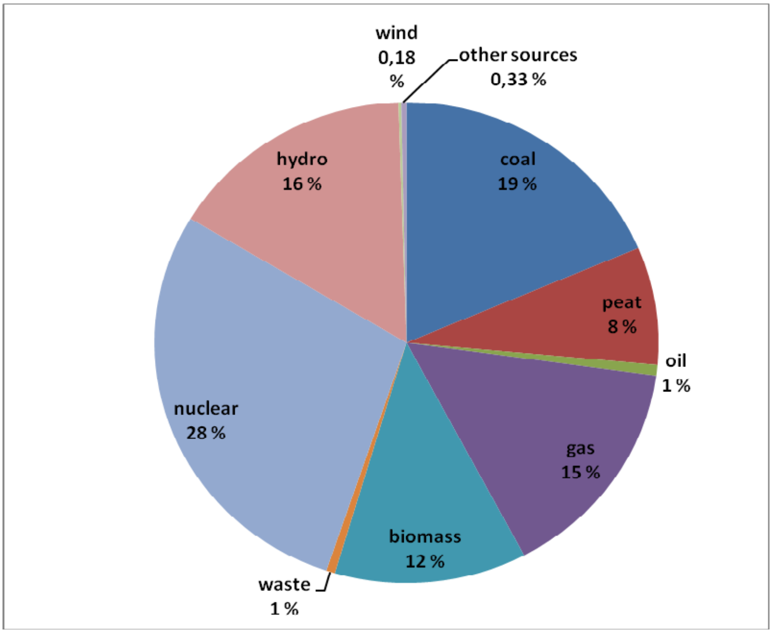


Figure C1. Electricity production profile of Finnish grid electricity (five-year average).

Some chemicals and other raw materials were assumed to be manufactured in Europe; in the gravure case, the manufacturing of paper and printing was modelled to take place in Europe too. Therefore an average European electricity mix was needed in the study. For European electricity, a module from Ecoinvent was applied. The emission factor for European electricity is 500 kg CO_2eq / MWh. Ecoinvent does not include the information on the European electricity production mix in its background data. Hence, we could not carry out any analysis of the details leading to the emission factor for European electricity. According to the IEA Statistics (2008), however, the difference between the European and Finnish figures is mainly due to higher shares of fossil energy sources in the European energy production profiles and due to the high share accounted for by efficient combined heat and power production (CHP) in Finland.

The following figure (Figure C2) presents the five-year average heat production profile for Finnish heat. The emission factor for Finnish average heat is 78 kg CO_2eq/GJ.

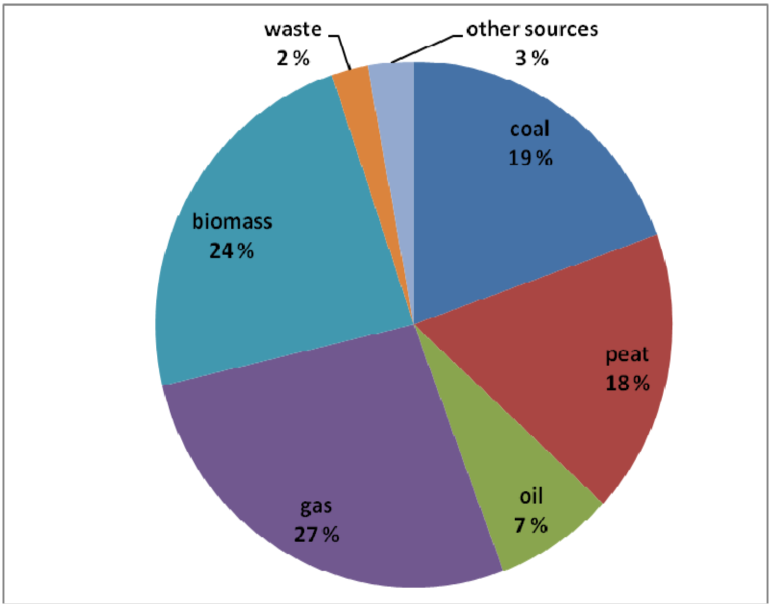
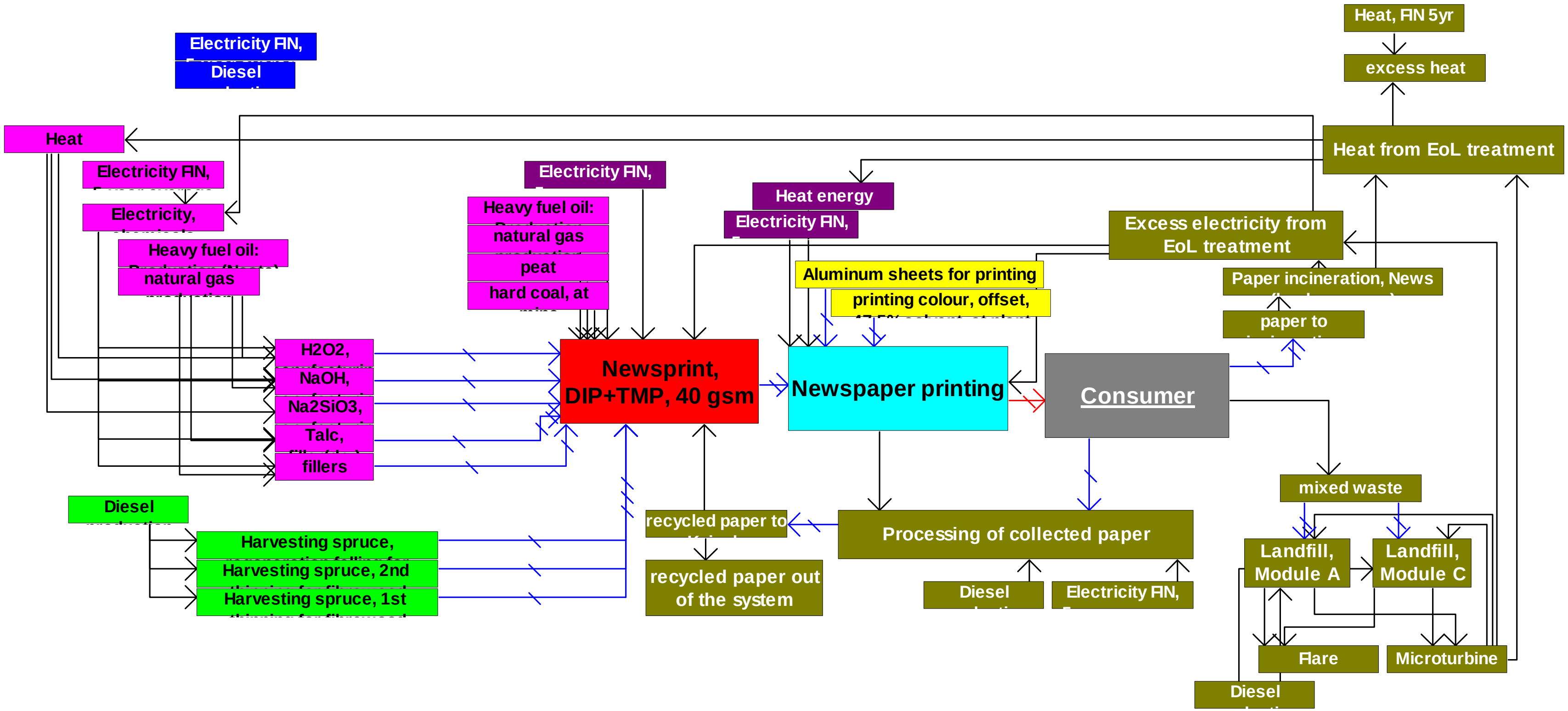


Figure C2. Heat production profile for five-year average Finnish heat.

For European cases, the average heat production mix of OECD Europe was applied. The emission factor for OECD Europe heat is 72 kg CO_2eq./GJ. The emission factor for European heat is lower than for Finnish heat because statistics for European heat include 23% unspecified heat, and in the study this share is treated as emission free. However, this does not contribute greatly to the results since OECD heat is needed only in the manufacturing of few chemicals and in calculations of avoided emissions in the gravure case.

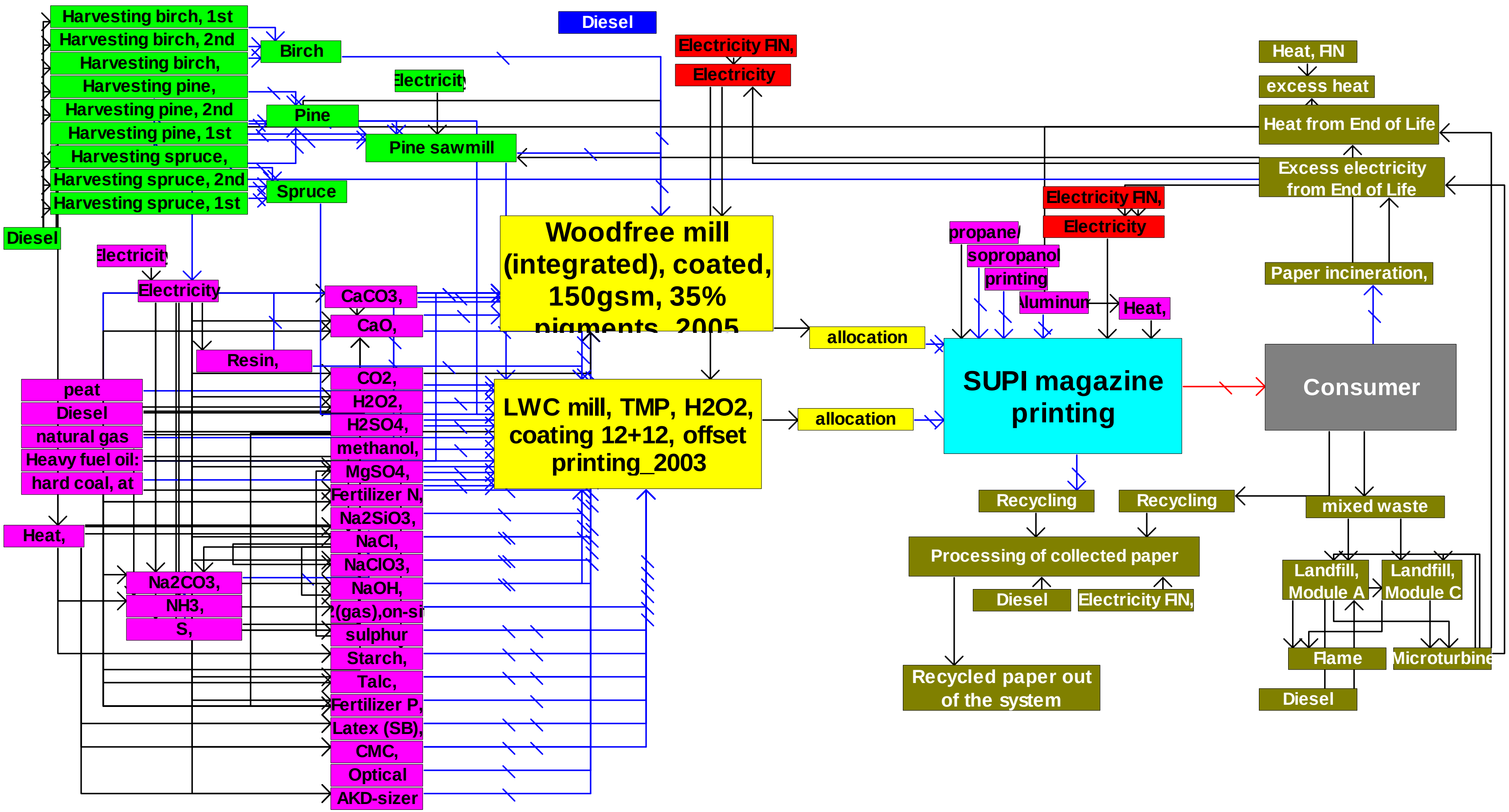
Appendix D: LCI flow sheets

Chapter 5: Coldset offset printed newspaper

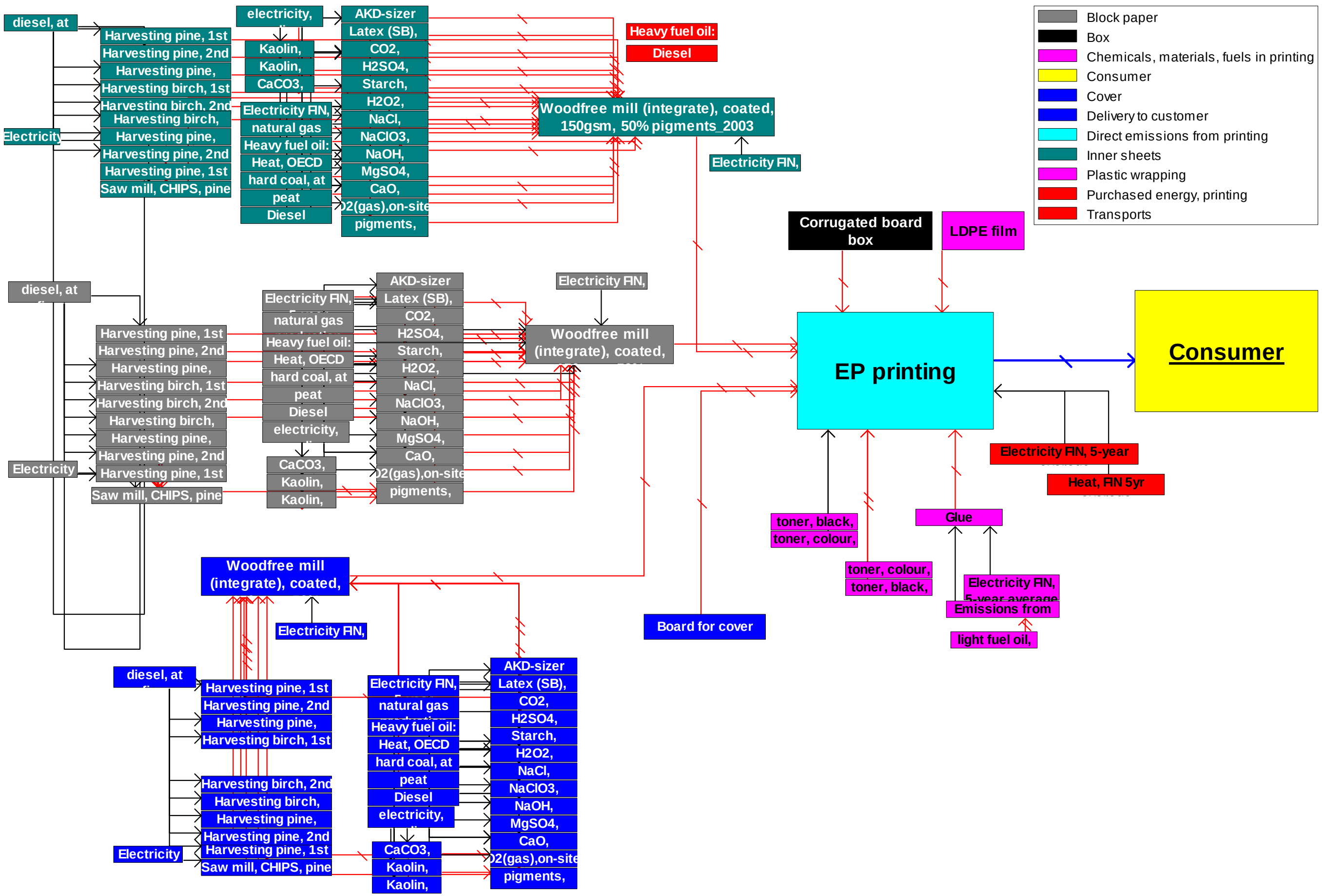


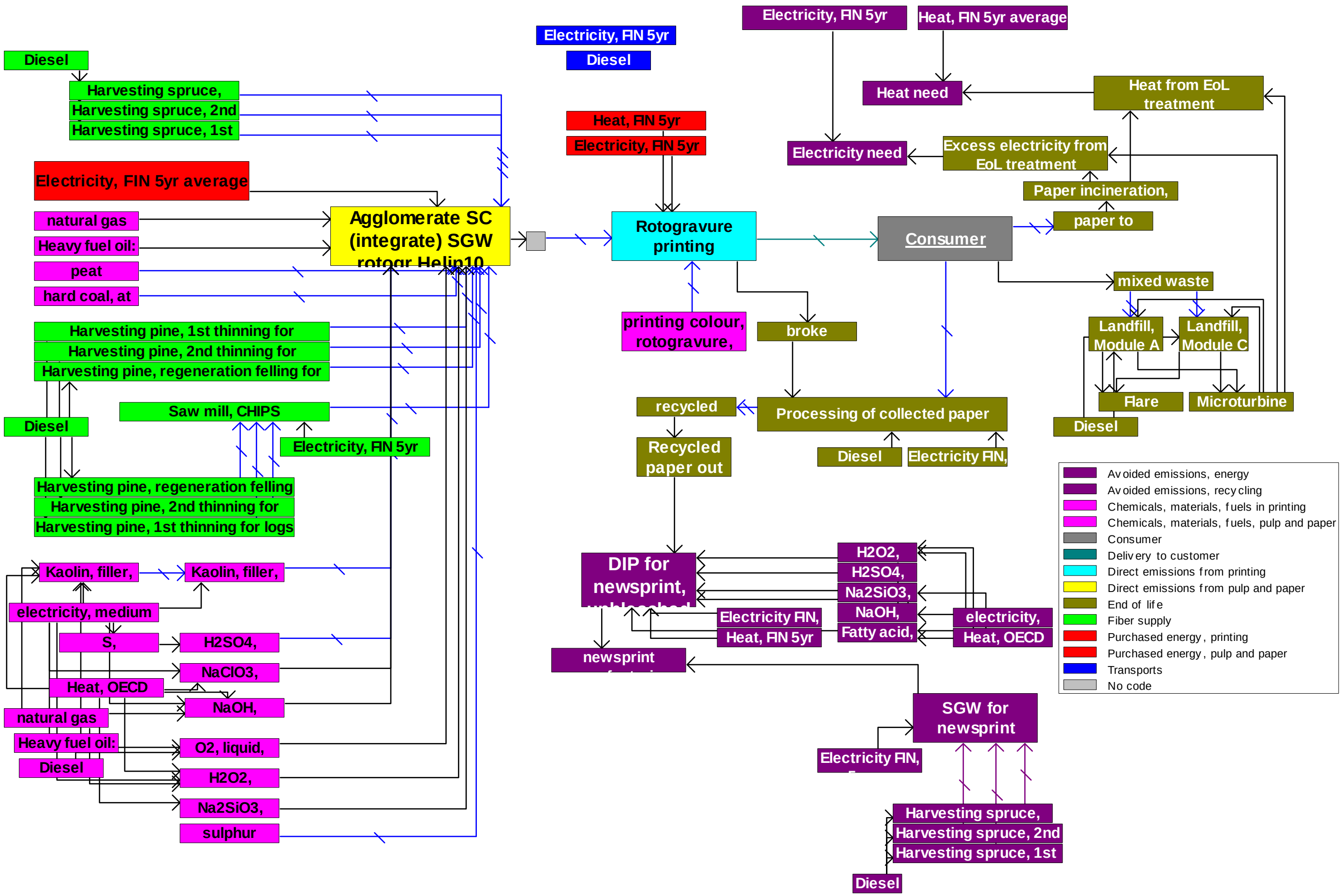
D1

Appendix C: Energy modules used in the study

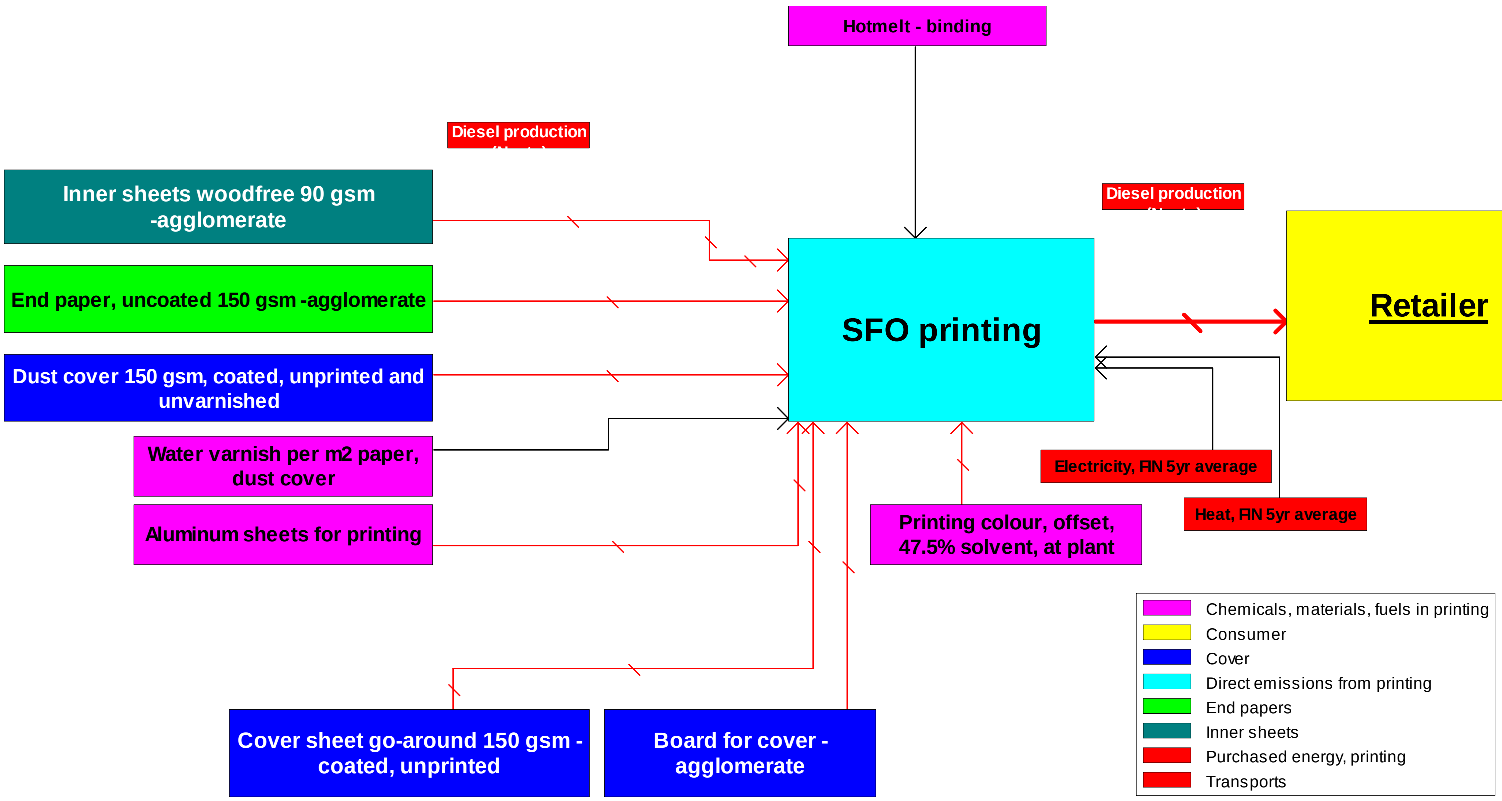

Harvesting birch, 1st
Harvesting birch, 2nd
Harvesting birch,
Harvesting pine,
Harvesting pine, 2nd
Harvesting pine, 1st
Harvesting spruce,
Harvesting spruce, 2nd
Harvesting spruce, 1st
Diesel
Birch
Pine
Spruce
Diesel
Electricity FIN,
Electricity
Electricity
Pine sawmill
Heat, FIN
excess heat
Heat from End of Life
Excess electricity from End of Life
Woodfree mill (integrated), coated, 150gsm, 35% pigments_2005
LWC mill, TMP, H2O2, coating 12+12, offset printing_2003
Electricity
Electricity
CaCO3,
CaO,
Resin,
CO2,
H2O2,
H2SO4,
methanol,
MgSO4,
Fertilizer N,
Na2SiO3,
NaCl,
NaClO3,
NaOH,
(gas),on-si
sulphur
Starch,
Talc,
Fertilizer P,
Latex (SB),
CMC,
Optical
AKD-sizer
peat
Diesel
natural gas
Heavy fuel oil:
hard coal, at
Heat,
Na2CO3,
NH3,
S,
allocation
allocation
propane/
sopropanol
printing
Aluminum
Electricity FIN,
Electricity
Heat,
SUPI magazine printing
Consumer
Paper incineration,
Recycling
Recycling
mixed waste
Processing of collected paper
Diesel
Electricity FIN,
Recycled paper out of the system
Landfill, Module A
Landfill, Module C
Flame
Microturbine
Diesel

Chapter 7: Electrophotography printed photobook




Diesel
Harvesting spruce,
Harvesting spruce, 2nd
Harvesting spruce, 1st
Electricity, FIN 5yr average
natural gas
Heavy fuel oil:
peat
hard coal, at
Agglomerate SC (integrate) SGW rotogr Helin10
Electricity, FIN 5yr
Diesel
Heat, FIN 5yr
Electricity, FIN 5yr
Rotogravure printing
printing colour, rotogravure,
Harvesting pine, 1st thinning for
Harvesting pine, 2nd thinning for
Harvesting pine, regeneration felling for
Diesel
Saw mill, CHIPS
Electricity, FIN 5yr
Harvesting pine, regeneration felling
Harvesting pine, 2nd thinning for
Harvesting pine, 1st thinning for logs
Kaolin, filler,
Kaolin, filler,
electricity, medium
S,
H2SO4,
NaClO3,
Heat, OECD
NaOH,
natural gas
Heavy fuel oil:
Diesel
O2, liquid,
H2O2,
Na2SiO3,
sulphur
Electricity, FIN 5yr
Heat, FIN 5yr average
Heat need
Heat from EoL treatment
Electricity need
Excess electricity from EoL treatment
Paper incineration,
paper to
Consumer
mixed waste
Landfill, Module A
Landfill, Module C
Flare
Microturbine
Diesel
broke
recycled
Processing of collected paper
Recycled paper out
Diesel
Electricity FIN,
DIP for newsprint, unbleached
H2O2,
H2SO4,
Na2SiO3,
NaOH,
Fatty acid,
Electricity FIN,
Heat, FIN 5yr
electricity,
Heat, OECD
newsprint
SGW for newsprint
Electricity FIN,
Harvesting spruce,
Harvesting spruce, 2nd
Harvesting spruce, 1st
Diesel
Avoided emissions, energy
Avoided emissions, recycling
Chemicals, materials, fuels in printing
Chemicals, materials, fuels, pulp and paper
Consumer
Delivery to customer
Direct emissions from printing
Direct emissions from pulp and paper
End of life
Fiber supply
Purchased energy, printing
Purchased energy, pulp and paper
Transports
No code

Chapter 9: Sheetfed offset printed book



Appendix E: LCI tables

E1. NEWSPAPER

Table E1.1. The GHG emissions of the reference scenario for newspaper divided into each life cycle phase. Results presented in absolute CO_2eq emissions [kg CO_2eq/tonne] and as a share of the life cycle [%]. Total emissions presented for cradle-to-gate and cradle-to-grave.

Life cycle stage	**Emissions**	**Share of total emissions**	
	kg CO_2e/tonne	**Cradle-to-gate [%]**	**Cradle-to-grave [%]**
Fibre supply	6	1%	1%
Chemicals, materials, fuels in pulp and paper	39	5%	4%
Direct emissions from pulp and paper	182	25%	17%
Purchased energy in pulp and paper	333	46%	31%
Chemicals, materials, fuels in printing	39	5%	4%
Direct emissions from printing	0	0%	0%
Purchased energy in printing	93	13%	9%
Other transports	26	4%	2%
Delivery to customer	174		16%
End of life	175		16%
Total	1066	(718 kg)	(1066 kg)

Table E1.2. Greenhouse gas emissions [kg CO_2eq/tonne$_{newspaper}$] produced over the life cycle of a newspaper in different scenarios.

Life cycle stage	**LF high**	**LF low**	**LF high green**	**LF low green**
Fibre supply	6	6	6	6
Chemicals, materials, fuels in pulp and paper	39	39	35	35
Direct emissions from pulp and paper	182	182	182	182
Purchased energy in pulp and paper	333	337	24	25
Chemicals, materials, fuels in printing	39	39	39	39
Direct emissions from printing	0	0	0	0
Purchased energy in printing	93	94	7	7
Delivery to customer	174	174	174	174
Other transports	26	26	26	26
End of life	175	-6	174	-7
Total	1066	890	666	485

Table E1.3. Nitrogen oxides (NOx) produced [kg/tonne$_{newspaper}$] over the life cycle of a newspaper in different scenarios.

Life cycle stage	**LF high**	**LF low**	**LF high green**	**LF low green**
Fibre supply	0.05	0.05	0.05	0.05
Chemicals, materials, fuels in pulp and paper	0.12	0.12	0.12	0.12
Direct emissions from pulp and paper	0.48	0.48	0.48	0.48
Purchased energy in pulp and paper	0,64	0,64	0,36	0.37
Chemicals, materials, fuels in printing	0.09	0.09	0.09	0.09
Direct emissions from printing	0	0	0	0
Purchased energy in printing	0.18	0.18	0.10	0.10
Delivery to customer	1.40	1.40	1.40	1.40
Other transports	0.36	0.36	0.36	0.36
End of life	0.09	0.10	0.09	0.10
Total	3.40	3.42	3.04	3.05

Table E1.4. Sulphur dioxides (SO_2) produced [kg/tonne$_{newspaper}$] over the life cycle of a newspaper in different scenarios.

Life cycle stage	**LF high**	**LF low**	**LF high green**	**LF low green**
Fibre supply	0.004	0.004	0.004	0.004
Chemicals, materials, fuels in pulp and paper	0.25	0.25	0.25	0.25
Direct emissions from pulp and paper	0.05	0.05	0.05	0.05
Purchased energy in pulp and paper	0.47	0.47	0.23	0.24
Chemicals, materials, fuels in printing	0.13	0.13	0.13	0.13
Direct emissions from printing	0	0	0	0
Purchased energy in printing	0.13	0.13	0.07	0.07
Delivery to customer	0.001	0.001	0.001	0.001
Other transports	0.005	0.005	0.005	0.005
End of life	-0.004	0.003	-0.005	0.002
Total	1.04	1.06	0.74	0.75

Table E1.5. Particulate matter (TSP) produced [kg/tonne$_{newspaper}$] over the life cycle of a newspaper in different scenarios.

Life cycle stage	LF high	LF low	LF high green	LF low green
Fibre supply	0.004	0.004	0.004	0.004
Chemicals, materials, fuels in pulp and paper	0.03	0.04	0.03	0.03
Direct emissions from pulp and paper	0.11	0.11	0.11	0.11
Purchased energy in pulp and paper	0.06	0.06	0.07	0.07
Chemicals, materials, fuels in printing	0.04	0.03	0.04	0.04
Direct emissions from printing	0	0	0	0
Purchased energy in printing	0.02	0.02	0.02	0.02
Delivery to customer	0.07	0.07	0.07	0.07
Other transports	0.004	0.004	0.004	0.004
End of life	0.01	0.01	0.01	0.01
Total	0.34	0.34	0.35	0.35

Table E1.6. Volatile organic compounds (VOC) produced [kg/tonne$_{newspaper}$] over the life cycle of a newspaper. Variation of VOC emissions in different scenarios is negligible.

Life cycle stage / Emissions to air	VOC [kg/tonne]
Fibre supply	0.000
Chemicals, materials, fuels in pulp and paper	0.083
Direct emissions from pulp and paper	
Purchased energy in pulp and paper	0.002
Chemicals, materials, fuels in printing	0.058
Direct emissions from printing	0.260
Purchased energy in printing	0.001
Delivery to customer	
Other transports	0.001
End of life	0.001
Total	0.40

Table E1.7. Emissions to water produced over the life cycle of a newspaper. Variation of water emissions in different scenarios is negligible. Results presented per tonne of newspapers.

Life cycle stage	COD	N,tot	P,tot	TSS	AOX
	kg	kg	kg	kg	g
Fibre supply	0.0003	0	0	0	0
Chemicals, materials, fuels in pulp and paper	0.01	0	0.00007	0.004	0
Direct emissions from pulp and paper	4.80	0.08	0.01	0.8	0
Purchased energy in pulp and paper	0.002	0	0.00002	0.003	0
Chemicals, materials, fuels in printing	0.23	0.07	0.003	0.03	0.0025
Direct emissions from printing	0	0	0	0	0
Purchased energy in printing	0.001	0.00001	0.00001	0.001	0
Delivery to customer	0	0	0	0	0
Other transports	0.001	0	0	0	0
End of life	0	0	0	0	0
Total	5.04	0.16	0.0173	0.85	0.0025

E2. MAGAZINE

Table E2.1. Greenhouse gas emissions [kg CO_2eq/tonne$_{magazine}$] produced over the life cycle of a magazine in different scenarios and with different allocations.

Life cycle stage/scenario	LF high	LF low	LF high green	LF high alloc	LF high AE
Fibre supply	37	38	37	14	37
Chemicals, materials, fuels in pulp and paper manufacturing	108	108	108	39	109
Direct emissions from pulp and paper	205	205	205	75	205
Purchased energy in pulp and paper manufacturing	507	512	507	182	507
Chemicals, materials, fuels in printing	79	79	79	79	79
Direct emissions from printing	97	97	97	97	97
Purchased energy in printing	108	109	8	108	108
Delivery to customer	94	94	94	94	94
Transports	44	44	36	23	44
End of life	209	27	209	195	209
Avoided emissions	0	0	0	0	-106
Total	1488	1312	1380	905	1382

Table E2.2. Nitrogen oxides (NOx) produced [kg/tonne$_{magazine}$] over the life cycle of a magazine in different scenarios and with different allocation methods.

Life cycle stage / Emissions to air	LF high	LF low	LF high green	LF high alloc	LF high AE
Fibre supply	0.23	0.23	0.23	0.08	0.225
Chemicals, materials, fuels in pulp and paper manufacturing	0.32	0.33	0.32	0.12	0.326
Direct emissions from p&p	0.99	0.99	0.99	0.36	0.985
Purchased energy in pulp and paper manufacturing	0.97	0.98	0.97	0.35	0.969
Chemicals, materials, fuels in printing	0.19	0.13	0.13	0.13	0.192
Direct emissions from printing	0.20	0.20	0.20	0.20	0.200
Purchased energy in printing	0.21	0.21	0.12	0.21	0.206
Delivery to customer	0.73	0.73	0.73	0.73	0.728
Transports	0.63	0.63	0.53	0.35	0.628
End of life	0.07	0.07	0.07	0.05	0.068
Avoided emissions	0	0	0	0	-0.638
Total	4.53	4.48	4.27	2.57	3.89

Table E2.3. Sulphur dioxides (SO_2) produced [kg/tonne$_{magazine}$] over the life cycle of a magazine in different scenarios and with different allocations.

Life cycle stage / Emissions to air	**LF high**	**LF low**	**LF high green**	**LF high alloc**	**LF high AE**
Fibre supply	0.04	0.04	0.04	0.02	0.042
Chemicals, materials, fuels in pulp and paper manufacturing	0.35	0.35	0.35	0.13	0.349
Direct emissions from pulp and paper	0.16	0.16	0.16	0.06	0.162
Purchased energy in pulp and paper manufacturing	0.71	0.72	0.71	0.26	0.714
Chemicals, materials, fuels in printing	0.35	0.19	0.19	0.19	0.351
Direct emissions from printing	0	0	0	0	0
Purchased energy in printing	0.15	0.15	0.08	0.15	0.152
Delivery to customer	0.00		0.0005	0.00	0.001
Transports	0.01	0.01	0.01	0.00	0.007
End of life	0.03	0.04	0.03	0.01	0.034
Avoided emissions	0	0	0	0	0.078
Total	1.81	1.66	1.57	0.81	1.89

Table E2.4. Particulate matter (TSP) produced [kg/tonne$_{magazine}$] over the life cycle of a magazine in different scenarios and with different allocations.

Life cycle stage / Emissions to air	**LF high**	**LF low**	**LF high green**	**LF high alloc**	**LF high AE**
Fibre supply	0.01	0.01	0.01	0.00	0.013
Chemicals, materials, fuels in pulp and paper manufacturing	0.10	0.10	0.10	0.04	0.100
Direct emissions from p&p	0.26	0.26	0.26	0.10	0.259
Purchased energy in pulp and paper manufacturing	0.09	0.09	0.09	0.03	0.087
Chemicals, materials, fuels in printing	0.06	0.06	0.06	0.06	0.058
Direct emissions from printing	0	0	0	0	0
Purchased energy in printing	0.02	0.02	0.02	0.02	0.018
Delivery to customer	0.07	0.07	0.07	0.07	0.067
Transports	0.01	0.01	0.01	0.00	0.008
End of life	0.01	0.01	0.01	0.01	0.007
Avoided emissions	0	0	0	0	-0.030
Total	0.62	0.62	0.62	0.32	0.59

Table E2.5. Volatile organic compounds (VOC) produced [kg/tonne$_{magazine}$] over the life cycle of a magazine in different scenarios and with different allocations.

Life cycle stage / Emissions to air	**LF high**	**LF low**	**LF high green**	**LF high alloc**	**LF high AE**
Fibre supply	0.07	0.065	0.07	0.02	0.065
Chemicals, materials, fuels in pulp and paper manufacturing	0.15	0.154	0.15	0.06	0.156
Direct emissions from p&p	0	0	0	0	0
Purchased energy in pulp and paper manufacturing	0.003	0.004	0.003	0.001	0.003
Chemicals, materials, fuels in printing	0.15	0.146	0.15	0.15	0.146
Direct emissions from printing	0.60	0.60	0.60	0.60	0.60
Purchased energy in printing	0.001	0.001	0.001	0.001	0.001
Delivery to customer	0	0	0	0	0
Transports	0.002	0.002	0.001	0.001	0.002
End of life	0.001	0.001	0.001	0.001	0.001
Avoided emissions	0	0	0	0	-0.050
Total	0.972	0.973	0.972	0.830	0.925

Table E2.6. Emissions to water (COD, Ntot) (kg/tonne magazine) produced over the life cycle of a magazine with different allocation methods. Variation in landfill characteristics and in electricity production has a negligible contribution to emissions to water.

Life cycle stage / Emissions to water	**COD**			**N,tot**		
Kg/tonne magazine	**LF high**	**LF high, alloc.**	**LF high, AE**	**LF high**	**LF high, alloc.**	**LF high, AE**
Fibre supply	0.0066	0.0024	0.0066	0.0000087	0.0000087	0.0000087
Chemicals, materials, fuels in pulp and paper manufacturing	0.057	0.021	0.057	0.00092	0.00092	0.00092
Direct emissions from pulp and paper	10.16	3.74	10.16	0.127	0.127	0.127
Purchased energy in pulp and paper	0.0035	0.0012	0.0035	0.000032	0.000032	0.000032
Chemicals, materials, fuels in printing	1.28	1.28	1.28	0.12	0.12	0.121
Purchased energy in printing		0.00074	0.00074	0	0	0.0000068
Delivery to customer	0.00074			0.0000068	0.0000068	
Other transport	0.0026	0.00078	0.0026	0.000011	0.000011	0.000011
End of life	0.00021	0.00014	0.00021	0.0000020	0.0000020	0.0000020
Avoided emissions			-1.92			-0.074
Total	11.5	5.0	9.6	0.25	0.25	0.17

Table E2.7. Emissions to water (Ptot, TSS) (kg/tonne magazine) produced over the life cycle of a magazine with different allocation methods. Variation in landfill characteristics and in electricity production has a negligible contribution to emissions to water.

Life cycle stage / Emissions to water	**P, tot**			**TSS**		
Kg/tonne magazine	**LF high**	**LF high, alloc.**	**LF high, AE**	**LF high**	**LF high, alloc.**	**LF high, AE**
Fibre supply	0.000082	0.000030	0.00009	0.0032	0.0012	0.0032
Chemicals, materials, fuels in pulp and paper	0.00018	0.000066	0.00018	0.023	0.0085	0.023
Direct emissions from pulp and paper	0.0024	0.00088	0.0024	0.81	0.30	0.81
Purchased energy in pulp and paper	0.000035	0.000012	0.000035	0.0041	0.0015	0.0041
Chemicals, materials, fuels in printing	0.0049	0.0049	0.0049	0.08	0.083	0.083
Purchased energy in printing	0	0.0000074	0.0000074	0	0.00087	0.00087
Delivery to customer	0.000007			0.00087		
Other transport	0	0	0	0.000015	0.0000044	0.000015
End of life	0.0000018	-0.000000048	0.0000018	0.000059	0.0000045	0.000059
Avoided emissions			-0.016			-0.67
Total	0.008	0.006	-0.008	0.93	0.39	0.26

Table E2.8. Emissions to water (AOX) (kg/tonne magazine) produced over the life cycle of a magazine with different allocation methods. Variation in landfill characteristics and in electricity production has a negligible contribution to emissions to water.

Life cycle stage / Emissions to water	**AOX**		
Kg/tonne magazine	**LF high**	**LF high, alloc.**	**LF high, AE**
Fibre supply	0	0	0
Chemicals, materials, fuels in pulp and paper	0.00000073	0.00000027	0.00000073
Direct emissions from pulp and paper	0.057	0.021	0.057
Purchased energy in pulp and paper	0	0	0
Chemicals, materials, fuels in printing	0.000005	0.000005	0.000005
Purchased energy in printing	0	0	0
Delivery to customer	0	0	0
Other transport	0	0	0
End of life	0	0	0
Avoided emissions	0	0	0
Total	0.057	0.021	0.057

E3. PHOTOBOOK

Table E3.1. Greenhouse gas emissions produced over the life cycle of a photobook (cradle to end-user) with and without packaging materials.

Life cycle stage	**With packaging**	**Without packaging**
	[kg CO_2eq]	**[kg CO_2eq]**
Per 1000 kg of photobooks:		
Inner sheets	514	514
Cover	315	315
End papers	40	40
Block paper	7	7
Chemicals, material, fuels in printing	159	159
Direct emissions from printing	0	0
Purch. energy, printing	268	268
Plastic wrapping	75	0
Box	190	0
Delivery to customer	404	404
Other transports	41	38
Total, 1000 kg of books (2000 pcs)	2013	1745
Per one book:		
	[kg CO_2eq]	**[kg CO_2eq]**
One book, 500 g	1.006	0.873
One book, 800 g	1.417	1.283

Table E3.2. Emissions to air (nitrogen oxides (NOx), sulphur dioxide (SO_2), total particulate matter (TSP) and volatile organic compounds (VOC) emissions) [kg/tonne$_{photobooks}$] produced over the life cycle of photobook (cradle-to-end user).

Life cycle stage / Emissions to air	NOx	SO_2	TSP	VOC
Inner sheets	1.8	0.9	0.4	0.12
Cover	0.5	0.6	0.1	0.12
End papers	0.2	0.1	0.1	0.01
Block paper	0.0	0.0	0.0	0.001
Chemicals, material, fuels in printing	0.4	0.0	0.1	0.09
Direct emissions from printing				
Purchased energy in printing	0.5	0.4	0.0	0.002
Plastic wrapping	0.1	0.2	0.0	0.14
Box	0.5	0.5	0.2	0.00002
Delivery to customer	3.0	0.0	0.0	
Other transport	0.4	0.1	0.0	0.002
Total	7.5	2.76	0.95	0.49

Table E3.3. Emissions to water [kg/tonne$_{photobooks}$] produced over the life cycle of photobook (cradle-to-customer).

Life cycle stage / Emissions to water	COD	N,tot	P,tot	TSS	AOX
Inner sheets	7.758	0.064	0.007	0.742	0.048
Cover	2.294	0.017	0.003	0.290	0.005
End papers	1.068	0.010	0.001	0.081	0.008
Block paper	0.175	0.002	0.000	0.013	0.001
Chemicals, material, fuels in printing	0.191	0.002	0.003	0.159	0.000
Direct emissions from printing					
Purchased energy in printing	0.002	0.000	0.000	0.002	0.000
Plastic wrapping	0.088	0.003	0.011	0.019	0.000
Box	2.126	0.066	0.006	0.338	0.002
Delivery to customer					
Other transport	0.002	0.000	0.000	0.000	0.000
Total	13.7	0.2	0.03	1.6	0.1

E4. LEAFLET

Table E4.1. Greenhouse gas emissions [kg CO_2eq/tonne$_{product}$] produced over the life cycle of a gravure printed leaflet in different scenarios

Life cycle stage/scenario	PRIM -FI FI FI	PRIM - EU FI FI	DIP74 - EU FI FI	PRIM FI EU EU	PRIM -FI FI EU
Fibre supply	29	31	4	29	29
Chemicals, materials, fuels in pulp and paper manufacturing	125	125	139	125	125
Direct emissions from pulp and paper	333	333	524	333	333
Purch. energy, pulp and paper manufacturing	446	894	93	446	446
Chemicals, materials, fuels in printing	110	110	110	110	110
Direct emissions from printing	-	-	-	-	-
Purchased energy in printing	210	210	210	286	210
Delivery to customer	153	153	153	153	153
Transports	54	79	66	77	77
End of life	171	171	171	304	304
Avoided emissions	-132	-132	-42	-221	-221
Total	1500	1975	1428	1643	1567

Note: Of the three digit codes (e.g. FI FI FI) the 1st stands for the location of paper manufacture, 2nd for printing and 3rd for end-use. PRIM = 100% primary fibres, DIP74 = 74% de-inked pulp.

E5. BOOK

Table E5.1. Greenhouse gas emissions produced over the life cycle of sheetfed offset printed hard-cover book (cradle to retailer) (kg/tonne product). Values are calculated for a book that weighs 500 grams.

Life cycle stage / GHG emissions	[kg CO_2eq. /book]
Inner sheets	0.50
Cover	0.07
End papers	0.01
Chemicals, material, fuels in printing	0.04
Direct emissions from printing	0
Purch. energy, printing	0.50
Other transports	0.04
Total	1.161

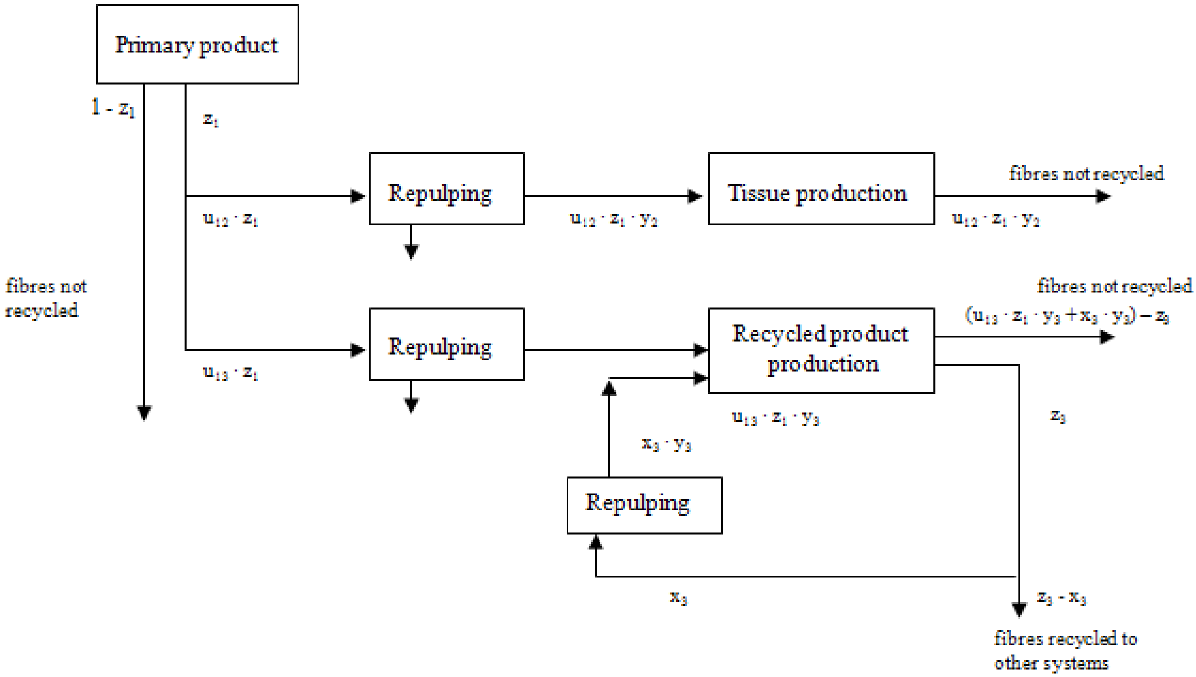
Appendix F: List of used data modules

Material	Source	From year
Modules used in all cases		
Harvesting wood	KCL EcoData	1998
Chemicals in pulp and paper manufacturing	KCL EcoData	1992–1999
Electricity, Finnish 5-yr average	IEA Statistics, KCL EcoData	5-yr average, 2002–2006
Heat, Finnish 5-yr average	IEA Statistics, KCL EcoData	5-yr average, 2002–2006
Pulp and paper manufacturing	KCL EcoData	2003–2010
Natural gas	Ecoinvent	2005
Heavy fuel oil	Neste Oil, Ecoinvent	2008, 2009
Hard coal	Ecoinvent	1990
Diesel	Neste Oil, Ecoinvent	2008
Peat	Kirkinen et al. 2008	2008
Landfill modules	SYKE	2007
Microturbine	Manfredi et al. 2009	2009
Processing of collected paper	SYKE, Finnish recycling company	2002
Newspaper		
Newsprint, DIP+TMP, 40 gsm	KCL EcoData, UPM-Kymmene Oyj	2003
Printing	Several Finnish printing houses	2007–2008
Aluminum sheets	EAA	2008
Printing ink, offset	Ecoinvent	2000
Newsprint incineration	KCL EcoData	1992
Magazine		
Printing	Several Finnish printing houses	2007–2008
Aluminum sheets	EAA	2008
Printing ink	Ecoinvent	2000
LWC paper incineration	KCL EcoData	1992

Electrophotography printed photo book		
Inner sheets (woodfree, coated 150 sm, 35% pigments)	KCL EcoData	2002
Cover sheet (woodfree, coated 150 gsm, 35% pigments)	KCL EcoData	2002
End papers (WF, uncoated, 80 gsm)	KCL EcoData	2002
Block paper (WF, uncoated, 80 gsm)	KCL EcoData	2002
Board for cover	KCL EcoData	2003, 2007
Printing	Several Finnish printing houses	2008
Toner, powder, at plant (colour + black)	Ecoinvent	2002
Corrugated board	KCL EcoData	2002
LDPE film for packaging	Ecoinvent	1993
Glue	KCL EcoData	2007
Gravure printed leaflet		
Electricity, European average	Ecoinvent	2007
Heat, European 5-yr average	IEA Statistics, KCL EcoData	5-yr average, 2002–2006
Deinking	KCL EcoData	2003
Rotogravure printing	EIPPCB 2007 , Enroth & Johans-son 2006, printing houses	2006–2007
Printing ink	Ecoinvent	2000
Sheetfed offset printed book		
Inner sheets (woodfree, uncoated 90 gsm)	KCL EcoData	2002
Cover sheet (woodfree, coated 150 gsm, 35% pigments)	KCL EcoData	2002
End papers (WF, uncoated, 80 gsm)	KCL EcoData	2002
Jacket (woodfree, coated 150 gsm, 35% pigments)	KCL EcoData	2002
Board for cover	KCL EcoData	2003, 2007
Printing	Several Finnish printing houses	2008
Printing ink, offset	Ecoinvent	2000
Aluminum sheets	EAA	2008
Water varnish	KCL EcoData	2008
Hot melt	KCL EcoData	2008

Appendix G: Principles of open-loop allocation

The calculation is based on an open-loop recycling example that can be found in ISO/TR 14049:2000 (8.3.3. Open-loop recycling). Example for a magazine.



Total number of uses for the fibre originating from the tray manufacturing process:

$$u = 1 + z_1 \cdot ((u_{12} + y_2) + (u_{13} \cdot y_3) \cdot (1/(1-(z_3 \cdot y_3)))),$$

In which	z1	= 0.83 (recycling rate of magazines)
	u12	= 0.118 (recycled to tissue)
	y2	= 0.95 (the yield of repulped fibres for recycled products)
	u13	= 0.882 (recycled again to recyclable products)
	y3	= 0.95 (the yield of repulped fibres for recycled products)
	z3=x3	= 0.82 (the fraction of recycled product that is recycled in a closed loop (average recycling rate of collected household paper))

u = 1 + z1 · ((u12+y2)+(u13 · y3) · (1 / (1 - (z3 · y3))))

=1 + 0.83 · [(0.118 · 0.95) + (0.882 · 0.95) · (1 / (1 - (0.82 · 0.95)))] = 4.19

→ u = 4.19

Now u is known, and an allocation factor for magazines can be calculated

(1 - z1) + (z1 / u) = (1 – 0.83) + (0.83 / 4.19) = 0.368

And an allocation factor for recycled products (going out from the system) is:

$$z_1 \cdot (u-1)/u = 0.83 \cdot (4.19-1)/4.19 = 0.632$$

→ 63.2% of emissions originating from magazine manufacturing are allocated to recycled paper.

Appendix H: Calculating carbon storage of products according to PAS 2050

Carbon storage was calculated for long-living products, i.e. a electrophotography printed photobook and a hardcover book. The assumptions used in calculating the biogenic carbon content of the products are presented in the table below.

General	Share of wood in dry matter [%]	Dryness [%]	Carbon content in reported dryness [%]	Carbon content as kg CO_2/product
Wood	100	100	50	
Mechanical/deinked pulp	100	100	50	
Chemical pulp	96	100	48	
Fillers and pigments	0	100	0	
A photobook, weight 500 g				
Woodfree, coated	45	96	21	0.213
Woodfree, uncoated	71	96	33	0.035
Cover board	100	96	48	0.276
Board for back	100	96	46	0.003
				≈ 530 g CO_2
A book				
Woodfree, uncoated (inner sheets, end papers)	71	96	33	0.780
Woodfree, coated (cover sheet, jacket)	45	96	21	0.012
Cover board	100	96	48	0.095
				≈ 880 g CO_2

Example of calculating biogenic carbon content and converting it to CO_2:

$$C_{DPPB} = C_{woodfree,coated} + C_{woodfree,uncoated} + C_{coverboard} + C_{board,back}$$

$$CO_{2,woodfree,coated} = C_{woodfree,coated} \times m_{woodfree,coated} \times \frac{M_{CO_2}}{M_C}$$

$$\rightarrow CO_2 = 0.21 \times 0.28 \,{}^{kg}\!/_{DPPB} \times \frac{44 \,{}^{kg}\!/_{kmol}}{12 \,{}^{kg}\!/_{kmol}} = 0.213 kg_{CO_2}$$

PAS 2050 gives further instructions on how biogenic carbon content can be utilized in carbon footprint calculations and credited from total emissions. The following formula is valid when a carbon storage benefit exists 25 years after the manufacture of the product:

$$Weighting\_factor = \frac{\sum_{i=1}^{100} x_i}{100}$$

In which

i = each year in which storage occurs
x = proportion of total storage remaining in any year i

When this formula is applied in the photobook case (when carbon storage benefit is calculated for one book for 50 years), the weighting factor can be calculated in the following way:

$$Weighting\_factor = \frac{50 \cdot 1 + 50 \cdot 0}{100} = \frac{50}{100} = 0.5$$

It should be noted that the carbon storage in this example is calculated for one book and it is assumed that after 50 years the book is destroyed immediately and the carbon is released back to the atmosphere. However, usually the situation is not that straightforward and the carbon in the book might be released slowly to the atmosphere (e.g. when degrading in a landfill). If multiple books are studied, some of them are probably stored for 50 years but some of them are stored only for a while and some for a very long time. In these cases, the weighting factor would be different. PAS 2050 gives an example of a calculation in which a product stores carbon for the first five years and then starts to degrade so that 20% of the carbon in the product is decreased per year over the next five years. The weighting factor is then:

$$Weighting\_factor = \frac{5 \cdot 1 + 0.8 + 0.6 + 0.4 + 0.2 + 0}{100} = 0.07$$

Thus, the total amount of biogenic carbon will be multiplied with a factor of 0.07 to get the weighted average impact of biogenic carbon stored in the product in a 100-year assessment period.

Appendix I: Used landfill modules

Two different landfills were examined in the study due to high uncertainty concerning the decomposition of paper in landfills as well as due to different gas collection rates and oxidation levels. The following table presents the studied landfill modules.

Parameter	Module LF high	Module LF low
DOC	0.4	0.39
DOC_f	0.5	0.16
Oxidation potential	0.1	0.82
Fraction of CH_4 recovered	60%	87%
Emissions to air		
CO_2 (fossil)	2.9	2.9
CO_2 (biogenic)	132	132
CH_4	48	0.9
VOC	0.003	0.003
Landfill gas	304	119

* DOC = degradable organic carbon
DOC_f = fraction of degradable organic carbon that degrades

Appendix J: LCIA results: Normalized impact category results

J1. NEWSPAPER

Table J1.1. LCIA results, normalized impact category results for the newspaper case, LF high scenario (basic case).

Newspaper, Lf high							
	Impact category						
Life cycle phase	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Particulate matter formation	Mineral resources depletion	Fossil resources depletion
Fibre supply	0.0005	0.0009	0	0.0009	0.001	0	0.001
Chemicals, materials, fuels in pulp and paper manufacturing	0.003	0.009	0.001	0.004	0.007	0.002	0.03
Purchased energy, pulp and paper	0.03	0.02	0.0003	0.01	0.02	0.08	0.04
Direct emissions from pulp and paper manufacturing	0.02	0.009	0.01	0.008	0.02	0	0
Chemicals, materials in printing	0.003	0.007	0.03	0.003	0.006	0.002	0.02
Purchased energy, printing	0.008	0.007	0.0001	0.003	0.005	0.02	0.01
Direct emissions from printing	0	0	0	0.005	0	0	0
Transports, all	0.02	0.03	0.0000002	0.03	0.03	0.00006	0.005
Transports: chemicals, other raw materials	0.00006	0.00007	0	0.00008	0.00007	0	0.0001
Transport: Delivery to customer	0.02	0.02	0	0.02	0.03	0	0
Transport: End of life transportation	0.001	0.002	0.0000002	0.002	0.002	0.00006	0.003
Transport: Paper to printing house	0.0008	0.003	0	0.003	0.003	0	0.002
Transport: Wood transportation	0.0003	0.001	0	0.001	0.0009	0	0.0007
End of life	0.02	0.001	-0.00002	0.003	0.002	0.0002	-0.001
Entire system	0.09	0.09	0.05	0.07	0.09	0.11	0.10

Appendix J: LCIA results: Normalized impact category results

Table J1.2. LCIA results, normalized impact category results for the newspaper case, LF high, green electricity scenario.

Newspaper, Lf high, green electricity							
	Impact category						
Life cycle phase	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Particulate matter formation	Mineral resources depletion	Fossil resources depletion
Fibre supply	0.0005	0.0009	0	0.0009	0.001	0	0.001
Chemicals, materials, fuels in pulp and paper manufacturing	0.003	0.009	0.0008	0.004	0.007	0.0005	0.03
Purchased energy, pulp and paper	0.002	0.01	0.0007	0.007	0.01	0.0008	0.0004
Direct emissions from pulp and paper manufacturing	0.02	0.009	0.01	0.008	0.02	0	0
Chemicals, materials in printing	0.003	0.007	0.03	0.003	0.006	0.002	0.02
Purchased energy, printing	0.0006	0.004	0.0002	0.002	0.004	0.0002	0.0001
Direct emissions from printing	0	0	0	0.005	0	0	0
Transport, all	0.02	0.03	0.0000005	0.03	0.03	0.0000006	0.002
End of life	0.02	0.001	-0.00001	0.003	0.002	0.000002	-0.001
Entire system	0.06	0.07	0.05	0.06	0.08	0.004	0.05

Table J1.3. LCIA results, normalized impact category results for the newspaper case, LF low scenario.

Newspaper, Lf low							
	Impact category						
Life cycle phase	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Particulate matter formation	Mineral resources depletion	Fossil resources depletion
Fibre supply	0.0005	0.0009	0	0.0009	0.001	0	0.001
Chemicals, materials, fuels in pulp and paper manufacturing	0.003	0.009	0.0008	0.004	0.007	0.002	0.03
Purchased energy, pulp and paper	0.03	0.02	0.0003	0.01	0.02	0.08	0.03
Direct emissions from pulp and paper manufacturing	0.016	0.009	0.01	0.008	0.02	0	0
Chemicals, materials in printing	0.003	0.007	0.03	0.003	0.006	0.002	0.02
Purchased energy, printing	0.008	0.007	0.00008	0.003	0.005	0.02	0.009
Direct emissions from printing	0	0	0	0.005	0	0	0
Transport, all	0.02	0.03	0.0000002	0.03	0.03	0.00006	0.002
End of life	-0.0006	0.002	-0.00001	0.002	0.002	0.0002	-0.0005
Entire system	0.08	0.09	0.05	0.07	0.09	0.1	0.1

Table J1.4. LCIA results, normalized impact category results for the newspaper case, LF low, green electricity scenario.

Newspaper, Lf low, green electricity							
	Impact category						
Life cycle phase	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Particulate matter formation	Mineral resources depletion	Fossil resources depletion
Fibre supply	0.0005	0.0009	0	0.0009	0.001	0	0.001
Chemicals, materials, fuels in pulp and paper manufacturing	0.003	0.009	0.0008	0.004	0.007	0.0005	0.03
Purchased energy, pulp and paper	0.002	0.01	0.0007	0.007	0.01	0.0008	0.0004
Direct emissions from pulp and paper manufacturing	0.02	0.009	0.01	0.008	0.02	0	0
Chemicals, materials in printing	0.003	0.007	0.03	0.003	0.006	0.002	0.02
Purchased energy, printing	0.001	0.004	0.0002	0.002	0.004	0.0002	0.0001
Direct emissions from printing	0	0	0	0.005	0	0	0
Transport, all	0.02	0.03	0.0000005	0.03	0.03	0.0000006	0.002
End of life	-0.0006	0.002	-0.00001	0.002	0.002	0.000002	-0.0008
Entire system	0.04	0.07	0.05	0.06	0.08	0.0	0.1

J2. MAGAZINE

Table J2.1. LCIA results, normalized impact category results for the magazine case, LF high (cut off allocation) scenario.

Magazine, LF high (cut off allocation)							
	Impact category						
Life cycle phase	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Particulate matter formation	Mineral resources depletion	Fossil resources depletion
Fibre supply	0.003	0.005	0.0003	0.004	0.005	0.001	0.004
Chemicals, materials, fuels in pulp and paper manufacturing	0.010	0.026	0.001	0.008	0.021	0.01	0.04
Purchased energy, pulp and paper	0.05	0.04	0.0004	0.02	0.03	0.12	0.05
Direct emissions from pulp and paper manufacturing	0.02	0.02	0.01	0.018	0.03	0	0.02
Chemicals, materials in printing	0.007	0.02	0.06	0.006	0.012	0.004	0.05
Purchased energy, printing	0.010	0.008	0.0001	0.004	0.006	0.03	0.01
Direct emissions from printing	0.009	0.003	0	0.01	0.003	0	0
Transport, all	0.01	0.02	0	0.02	0.03	0	0.008
End of life	0.02	0.002	0.00001	0.003	0.002	0.0003	0.002
Entire system	0.13	0.14	0.07	0.10	0.14	0.17	0.19

Table J2.2. LCIA resutls, normalized impact category results for the magazine case, LF low (cut off allocation) scenario.

Magazine, LF low (cut off allocation)							
	Impact category						
Life cycle phase	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Particulate matter formation	Mineral resources depletion	Fossil resources depletion
Fibre supply	0.003	0.005	0.0003	0.004	0.005	0.001	0.004
Chemicals, materials, fuels in pulp and paper manufacturing	0.01	0.03	0.001	0.008	0.02	0.01	0.04
Purchased energy, pulp and paper	0.05	0.04	0.0004	0.02	0.03	0.12	0.05
Direct emissions from pulp and paper manufacturing	0.02	0.02	0.01	0.02	0.03	0	0.02
Chemicals, materials in printing	0.007	0.02	0.06	0.006	0.01	0.004	0.05
Purchased energy, printing	0.01	0.008	0.0001	0.004	0.006	0.03	0.01
Direct emissions from printing	0.009	0.003	0	0.01	0.003	0	0
Transport, all	0.01	0.02	0	0.02	0.03	0	0.008
End of life	0.003	0.002	0.00002	0.001	0.002	0.0003	0.002
Entire system	0.12	0.14	0.07	0.10	0.14	0.17	0.19

Table J2.3. LCIA results, normalized impact category results for the magazine case, open-loop allocation scenario.

Magazine, open-loop allocation							
	Impact category						
Life cycle phase	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Particulate matter formation	Mineral resources depletion	Fossil resources depletion
Fibre supply	0.001	0.002	0.0001	0.002	0.002	0.0004	0.001
Chemicals, materials, fuels in pulp and paper manufacturing	0.004	0.01	0.0004	0.003	0.01	0.004	0.02
Purchased energy, pulp and paper	0.02	0.01	0.0002	0.01	0.01	0.04	0.02
Direct emissions from pulp and paper manufacturing	0.01	0.01	0.003	0.01	0.01	0	0.007
Chemicals, materials in printing	0.007	0.02	0.06	0.006	0.01	0.004	0.05
Purchased energy, printing	0.01	0.008	0.0001	0.004	0.006	0.03	0.01
Direct emissions from printing	0.009	0.003	0	0.01	0.003	0	0
Transport, all	0.01	0.02	0	0.02	0.02	0	0.003
End of life	0.02	0.001	0.0000002	0.002	0.001	0.0003	0.0005
Entire system	0.08	0.08	0.06	0.06	0.08	0.08	0.11

Table J2.4. LCIA results, normalized impact category results for the magazine case, avoided emissions (system expansion) scenario.

Magazine, avoided emissions							
	Impact category						
Life cycle phase	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Particulate matter formation	Mineral resources depletion	Fossil resources depletion
Fibre supply	0.003	0.005	0.0003	0.004	0.005	0.001	0.004
Chemicals, materials, fuels in pulp and paper manufacturing	0.01	0.03	0.001	0.008	0.02	0.01	0.04
Purchased energy, pulp and paper	0.05	0.04	0.0004	0.02	0.03	0.12	0.05
Direct emissions from pulp and paper manufacturing	0.02	0.02	0.009	0.02	0.03	0	0.02
Chemicals, materials in printing	0.007	0.02	0.06	0.006	0.01	0.004	0.05
Purchased energy, printing	0.01	0.008	0.0001	0.004	0.006	0.03	0.01
Direct emissions from printing	0.009	0.003	0	0.01	0.003	0	0
Transport, all	0.01	0.02	0	0.02	0.03	0	0.008
End of life	0.02	0.002	0.00001	0.003	0.002	0.0003	0.002
Deinking	0.02	0.02	0.004	0.008	0.01	0.02	0.02
Avoided emissions	-0.03	-0.03	-0.00035	-0.02	-0.02	-0.14	-0.04
Entire system	0.12	0.13	0.07	0.09	0.13	0.05	0.17

J3. PHOTOBOOK

Table J3.1. LCIA results, normalized impact category results for the electrophotography printed photobook.

Electrophotography printed photobook					
	Impact category				
Life cycle phase	Climate change	Terrestrial acidification	Freshwater eutrophication	Photochemical oxidant formation	Particulate matter formation
Inner sheet	0.05	0.06	0.03	0.04	0.06
First sheet	0.004	0.005	0.004	0.004	0.007
Cover	0.03	0.03	0.01	0.01	0.02
Block paper	0.001	0.0009	0.0007	0.0006	0.001
Plastic wrapping	0.007	0.01	0.1	0.005	0.007
Box	0.02	0.02	0.025	0.01	0.03
Purchased energy, printing	0.02	0.02	0.0002	0.01	0.02
Chemicals, materials, fuels in printing	0.01	0.03	0.03	0.01	0.02
Transport	0.004	0.01	0	0.007	0.008
Delivery to customer	0.04	0.05	0	0.05	0.05
Entire system	0.18	0.24	0.25	0.15	0.22
	Impact category				
Life cycle phase	Mineral resources depletion	Fossil resources depletion	Human toxicity	Terrestrial ecotoxicity	Freshwater ecotoxicity
Inner sheet	0.02	0.07	0.0006	0.00004	0.003
First sheet	0.002	0.01	0.00003	0.000002	0.0001
Cover	0.003	0.05	0.0007	0.00005	0.006
Block paper	0.0003	0.001	0.000005	0.0000004	0.00001
Plastic wrapping	0.001	0.03	0.0005	0.0001	0.05
Box	0.01	0.01	0	0	0
Purchased energy, printing	0.04	0.02	0.0000003	0.000000004	0.000000003
Chemicals, materials, fuels in printing	0.002	0.040	0.002	0.0003	0.04
Transport	0	0.008	0.0000003	0.000004	0.000004
Delivery to customer	0	0.000	0	0	0
Entire system	0.09	0.23	0.003	0.0005	0.1

Appendix K: Parameters used for microturbine in landfills

56% of the recovered landfill gas is assumed to be directed to a microturbine for energy conversion. The parameters used for microturbine are presented below.

Parameter	**Value**	**Unit**
Landfill gas (48% CH_4, 52% CO_2 of dry matter):		
Lower heating value	17.4 12.7	MJ/m^3 MJ/kg
Microturbine:		
Conversion efficiency	83% (44% heat, 39% electricity)	
Emissions to air:		
CO_2 (fossil)	0,46	kg/ton_{gas}
CO_2 (biogenic)	1436	kg/ton_{gas}
CH_4	0,24	kg/ton_{gas}
NO_x	0,32	kg/ton_{gas}
SO_2	0,28	kg/ton_{gas}
TSP	0,04	kg/ton_{gas}
VOC	0,01	kg/ton_{gas}
PAH	0,35	g/ton_{gas}

Source: Manfredi et al. 2009. Environmental assessment of gas management options at the Old Ämmässuo landfill by means of LCA-modeling (EASEWASTE). Waste management 29 (2009), pp. 1588–1594.

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Title

Carbon footprint and environmental impacts of print products from cradle to grave

Results from the LEADER project (Part 1)

Abstract

The report presents the main results of the LEADER project that was ongoing in Finland between the years 2007–2010. The aim of the project was to study the environmental impacts occurring during the life cycle of print products. The scope of the project was focused on printed media products.

In the study, life cycle assessments and carbon footprints were calculated for five case products: heatset offset printed magazine, coldset offset printed newspaper, sheetfed offset printed book, electrophotography printed photobook and rotogravure printed advertisement.

The environmentally extended input-output model ENVIMAT was applied to provide an estimate of the environmental impacts related to the production and consumption of print products in Finland. Additionally, the development of environmental performance within different printing methods is evaluated and the environmental indicators specific for the printing phase are discussed.

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